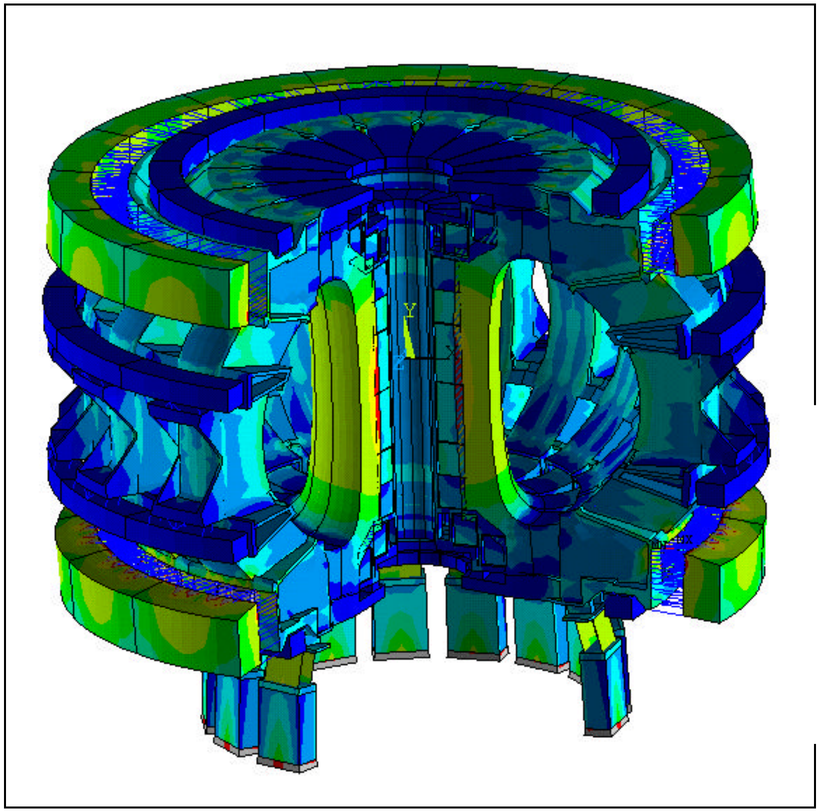
MIT PSFC

FIRE Fusion Ignition Research Experiment



FIRE Design Review

Magnet System Structural Analyses

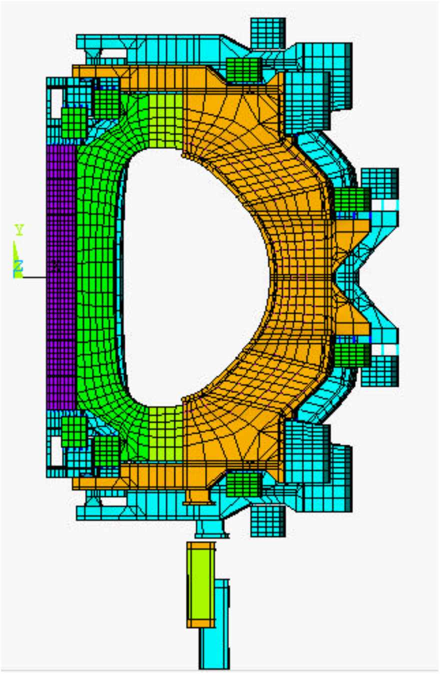
Princeton Plasma Physics Laboratory June 5-7
2001

Peter H. Titus
MIT Plasma Science and Fusion Center, Cambridge
MA under contract from Stone & Webster
Engineering Corporation

Stone & Webster A SHAW GROUP COMPANY

Mission: Qualify All FIRE Baseline and Variant Designs:

	FIRE	FIRE	FIRE*	
	Baseline Design W (wedged TF)	BW (bucked and wedged TF)	W (wedged TF)[1]	BW (bucked and wedged TF)[1]
TF Inner Leg Mat	BeCu	OFHC	BeCu	OFHC
R (m), a (m)	2.0, 0.525	2.0, 0.525	2.14, 0.595	2.14, 0.595
$B_{t(Ro)}$ (T), baseline (upgrade)	10(12)	10(12)	10 (12)	10(12)
flattop time (s)	~20(12)*	31(23)	~20(12)	~31(23)
TF Allowable(MPa)	700	300	700	300
TF Von Mises Stress	466(666)	230(326)	529 (762)	230(326)
Min. TF stress Factor of Safety (FS) (allowable/actual)[1]	**1.5 (1.05)**	**1.3 (.92)**	**1.3 (.92)**	**1.3 (.92)**
Wmag TF (GJ)	3.7(5.328)	3.7(5.328)	5.08(7.32)	5.08(7.32)
I_p (MA)	6.44(7.7)	6.44(7.7)	7.7 (8.25)	7.7 (8.25)
CS Peak Stress at PRE	294(354)	(228[1])	322(322)	(228[1])
CS Temp at PRE	83(85)	83(85)	88?(88)	88(88)
CS allowable at Pre[1]	345(347)	345(347)	344(344)	344(344)
CS F.S at Pre	**1.15(.98)**	**2.1(1.5)**	**1.07(1.07)**	**2.1(1.5)**
CS Peak Stress at EOB	182(332)	(30)	190(279)	(30)
CS Peak Temp (EOB)	159 (176)	159 (176)	177(227)	177(227)
CS Allowable (EOB)	313(305)	313(305)	304(280)	304(280)
CS F.S at EOB	**1.7(.92)**	**>10(10)**	**1.6(1.0)**	**>9(9)**
CS flattop time (s)	21(15)	21(15)	17.5(32??)	17.5(32??)
Fusion Power (MW)	~ 200	~ 200	150	150

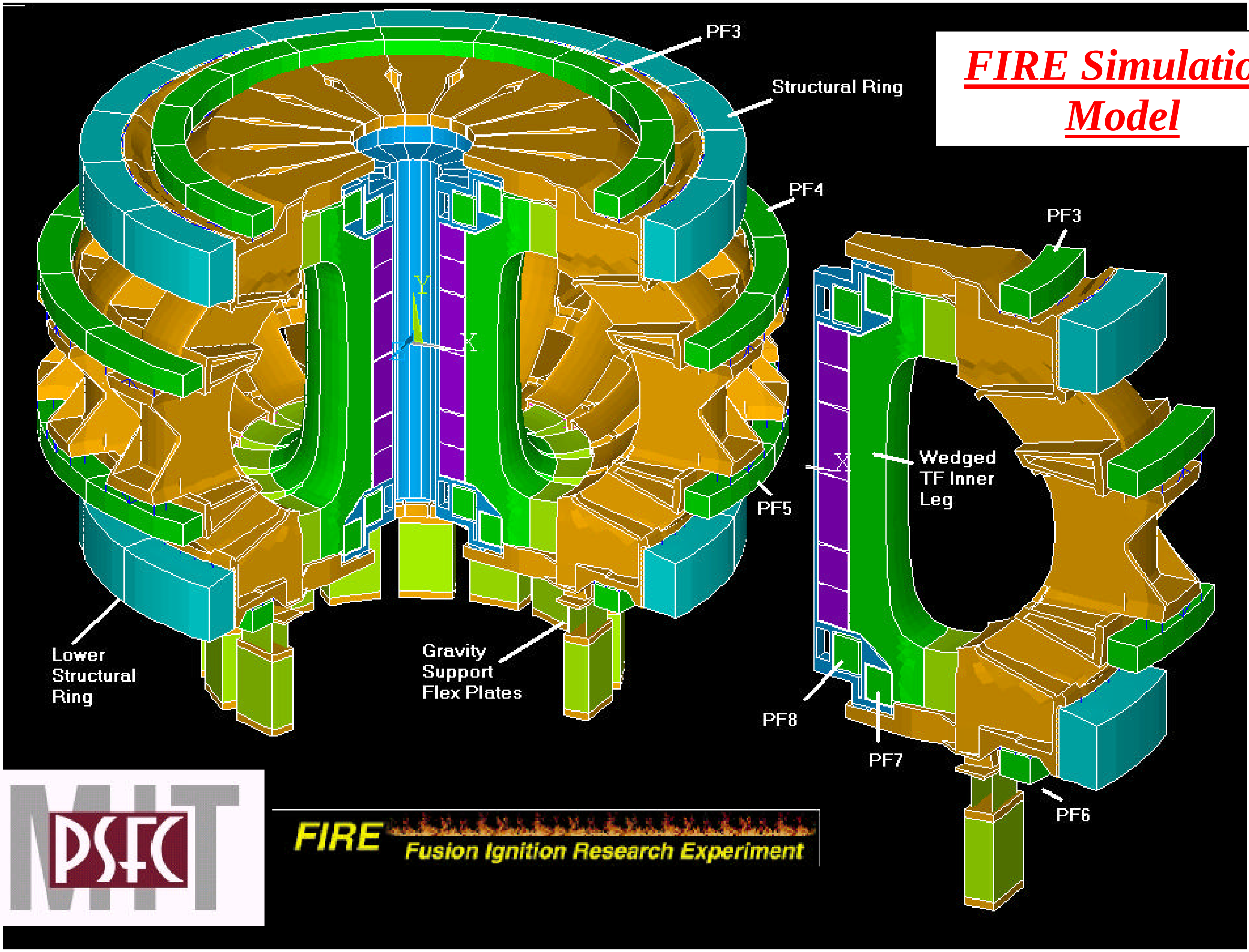


Baseline FIRE Model in front of FIRE* which is blue in this plot

TF Model build

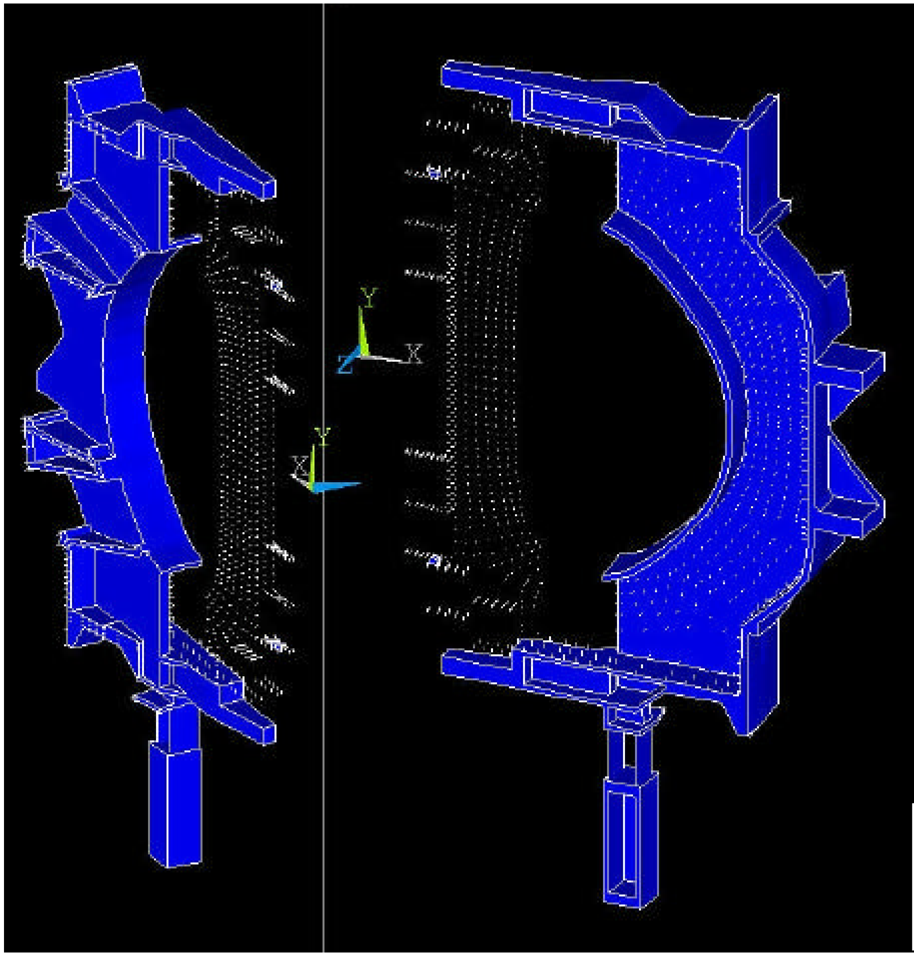
	FIRE	FIRE*
Inner Leg IR	.820	.910153m
Inner Leg OR	1.308	1.3996m
Outer Leg IR	3.4375	3.6926
Outer Leg OR	4.0388	4.3379

FIRE Simulation Model



FIRE Fusion Ignition Research Experiment

FIRE Simulation Model



- **Material and Geometric Non-Linearities**
- **Path Dependent Coulomb Friction**
- **Electromagnetic/Thermal Current Diffusion**

Gap Locations •TF Coil to Case
•RF Wedge Face
•Case-to-Case Wedge Face
•CS Segment-to Segment
•PF-Case Interface
•TF/CS Bucked Interface (If Applicable)

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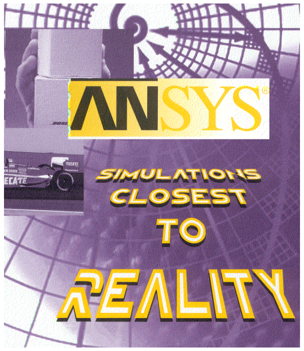
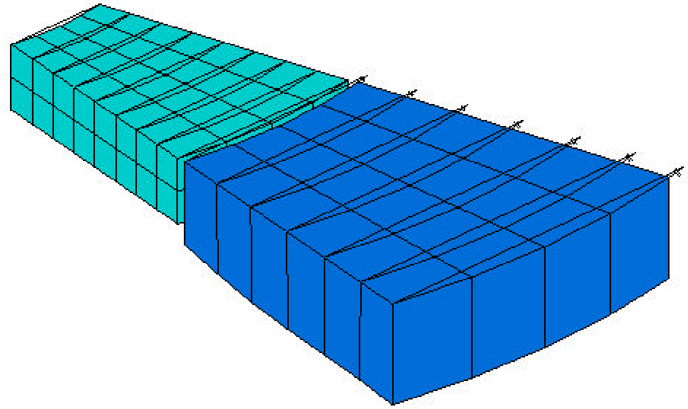


Leg and Case Gaps:

In the Non-Linear Model, Gaps are used at the Wedged Face.

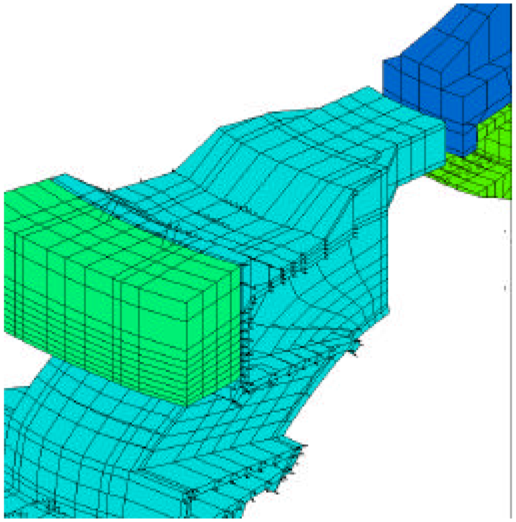
FIRE Fusion Ignition Research Experiment



Section Through CS and TF coils at the Equatorial plane.

Inner Legs are not Bonded, Only Friction Supports Shear.

Cyclic Symmetry is Obtained by Coupling the Gaps across to the Opposite Face, in a Cylindrical Coordinate System
Gaps Model Path Dependent Coulomb Friction, De-Wedging, and Separation, as in Initial Ring Preload



Case Model with Gap elements at the Parting Plane. Friction is the only shear transmission mechanism.

Summary of Available FIRE Scenarios

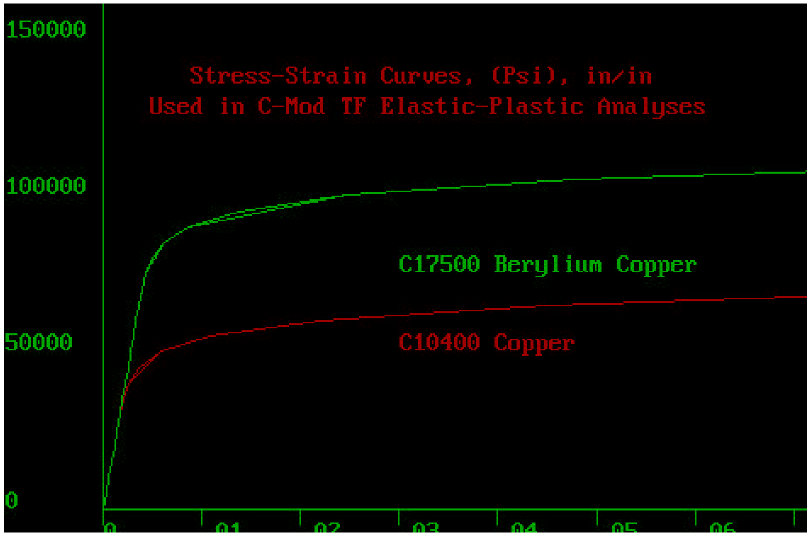
	S #	Ref	Originator	Date	Ro	Ip	Bt	δ	EOB-SOD (Sec)	Comments
*	15		Titus		2.14	8.25?	12?		?	Ave of #12 and #13
	14		Kessel	12/19/00	2.14	7.7	10		27	
	13		Kessel	12/17/00	2.14	7.7	10		27	
*	12		Kessel	12/02/00	2.14	7.7	10		27	
*	11		Kessel		2.0	7.6	11.5	.8	28	B&W
	10		Kessel	10/19/00	2.0	7.25	11.5	.7	28	B&W
*	9		Titus		2.0	7.7	12		19	
	8		Kessel	06/22/00	2.0	7.7	12		19	
	7		Kessel	06/21/00	2.0	7.7	12		19	
	6		Kessel		2.0	2.0	4		250	
*	5		Kessel	06/09/99	2.0	6.44	10		27	
	4		Kessel	06/08/99	2.0	6.44	10		27	
	3		Kessel		2.0	6.44	10		17	
	2		Kessel	06/03/99	2.0	6.44	10		17	
	1		Kessel		2.0	6.44	10			

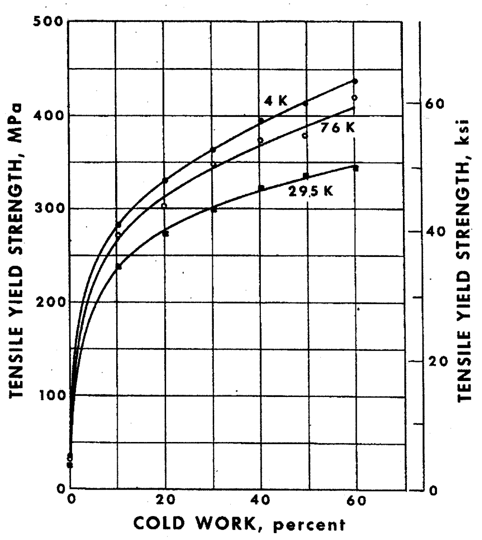
* Current Baseline Scenario for the Configuration it Represents

FIRE Fusion Ignition Research Experiment

Copper Properties Used For the TF and CS

	CS	TF
FIRE Wedged	**OFHC**	**68%BeCu**
FIRE B&W	**OFHC**	**OFHC**





NIST Data - Oxygen Free Copper Tensile Properties (4-300K)- C10100 - C10700 Cold Worked

Properties of Copper Beryllium Alloy C17510 [6]

	Yield, Mpa at RT	**Ult. Str. MPa at RT**	**Elec. Cond. % IACS at RT**	**% elong. At RT**
Hycon 3 HP^{TM} 68105	**724**	**800**	**68**	**14**

Hycon 3HP is a trademark of Brush-Wellman, Inc.

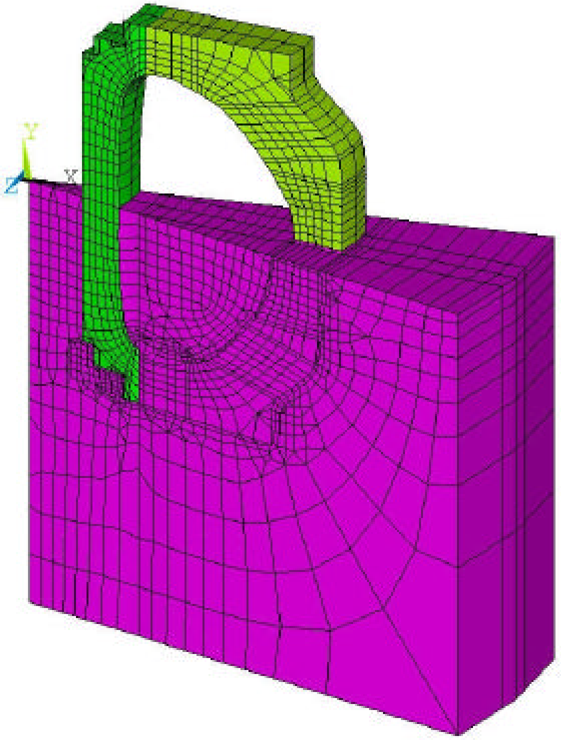
Tensile Properties for Magnet Structural Materials

Material	Yield 4 deg K (MPA)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (MPa)	Ultimate, 80 deg. K (MPa)	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	992[29]	1379[29]			275.8[29]	613[29]
316 LN SST Weld	724[29]	1110[29]			324[29]	482[29]
304 SST 50% CW	1613	1896	1344	1669	1089	1241
304 Stainless Steel (Bar,annealed)	404	1721	282	1522	234	640

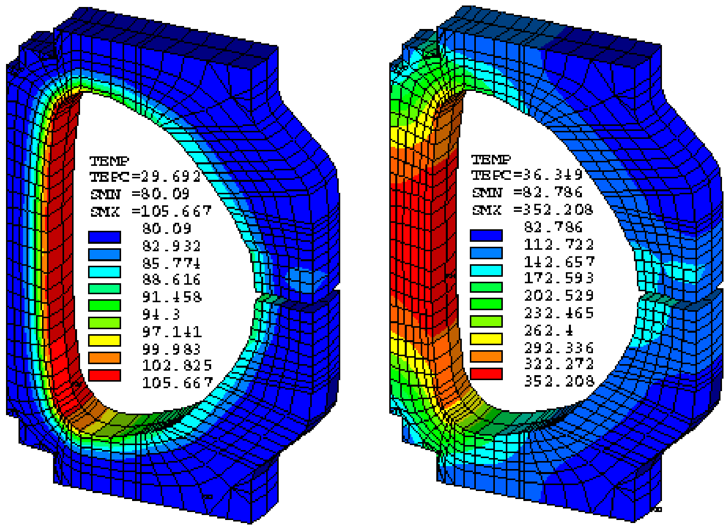
Primary Stress Allowables for Materials used in FIRE

68% IACS BeCu Cond	60% CW OFHC Cond	Cast 304SST	50%CW 304 SST
Sm=483 Mpa at RT	Sm=200 Mpa at RT	Sm=154 Mpa at RT	Sm=620Mpa at RT
Sm=497 Mpa at 77K	Sm=233 Mpa at 77K	Sm=188 Mpa at 77K	Sm=834Mpa at 80K

TF Electromagnetic-Thermal Current Diffusion Analysis



- ANSYS Coupled electromagnetic/ thermal analysis is used to solve the current diffusion problem.
- Model at left is shown with the upper half of air elements removed
- One-D Code is also used for pulse length studies



5 Sec, Early in Ramp-Up

48 sec, End of Flat-Top

FIRE TF Current/Thermal Diffusion Analysis Results, 77% IACS Material

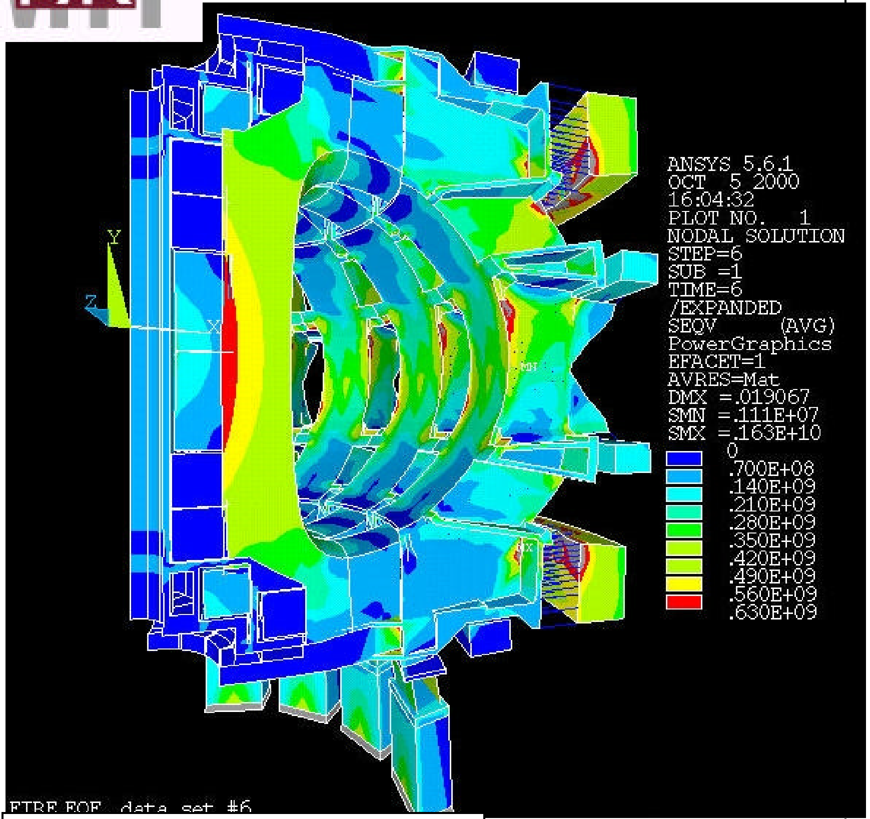
Zero-D Code Flat-Top Times

FIRE Flat Top Times (Feb 3 Dimensions, TF Central Column OR=1.308,IR=.820)
Simplified Calculations using Packing Fraction=.9 Nonuniformity=1.0, 80° Start, 370°K Temp Limit

Config	FIRE All Copper, Buck &Wedge	FIRE All Copper, Buck &Wedge	FIRE Baseline, Advanced Physics	FIRE 68%IACS BeCu TF	FIRE 68%IACS BeCu TF	FIRE 68%IACS BeCu TF	FIRE 68%IACS BeCu TF
TF Field	12T	12T	4T	10T	10T	12T	12T
IACS	100%	100%	77%	68%	68%	68%	68%
Nuc Heat	11 MW/m^3	0.0	0.0	11 MW/m^3	0.0	11 MW/m^3	0.0
Time	23 sec	40 sec	243 sec	18.5 sec	26 sec	12 sec	15 sec

FIRE OPTIONS TF Flat Top Times 68%IACS BeCu TF (Feb 3 Dimensions, TF Central Column OR=1.308,IR=.820),Simplified Calculations using Packing Fraction=.9 Nonuniformity=1.0, 80° Start, 370°K Temp Limit

TF Field	4T	8T	8T	10T	10T	12T	12T
Nuc Heat	0.0	7.5 MW/m^3	0.0	11 MW/m^3	0.0	11 MW/m^3	0.0
Time	214	31 sec	46sec	18.5 sec	26 sec	12 sec	15 sec



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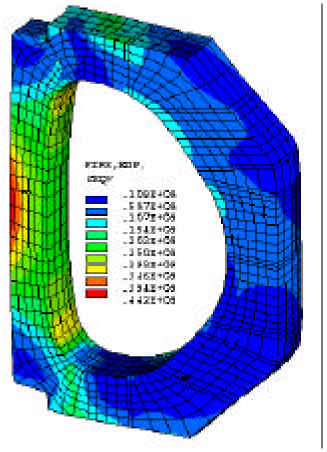
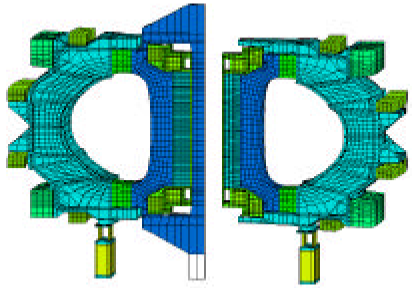
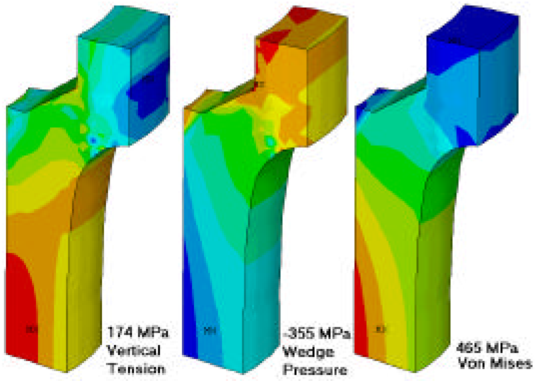


Typical TF Von Mises Stress for the 10T



Models With and Without Tierod

The Tie-rod applied to the TF improved it's stress by only 25 MPa, and was eliminated in favor of added space for CS coolant channels, leads and CS Tierods.



10T Wedged Configuration Inner Leg Stresses

The Wedged Version of FIRE is Characterized by Very Large Wedge Compressions

	Insulator Dose	Compressive stress	Von Mises	RT and 80°K Required Compressive Strength based on 2/3 Criteria
Plasma side 10T operation 2.0m machine	1.27e10 RAD	240 MPa	300 MPa	450 MPa
CS side 10T operation 2.0m machine	1.58e8 RAD	360 MPa	469 MPa	704 MPa
Plasma side 12T operation 2.0m machine	1.27e10 RAD	346 MPa	440 MPa	660 MPa
CS side 12T operation 2.0m machine	1.58e8 RAD	520 MPa	689 MPa	1033 MPa

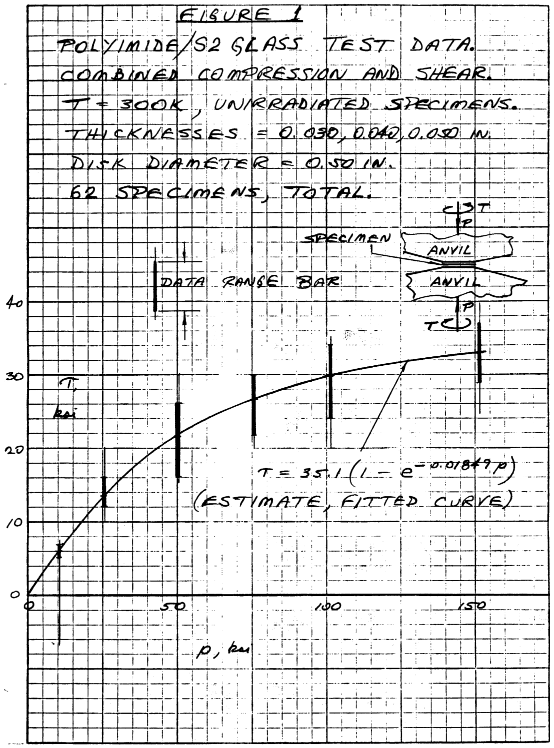


FIGURE 1

POLYIMIDE/S2 GLASS TEST DATA.
COMBINED COMPRESSION AND SHEAR.
T = 300K, UNIRRADIATED SPECIMENS.
THICKNESSES = 0.030, 0.040, 0.050 IN.
DISK DIAMETER = 0.50 IN.
62 SPECIMENS, TOTAL.

$\tau = 35.1(1 - e^{-0.01849 p})$
(ESTIMATE, FITTED CURVE)

From Ref. [30] Effect of Face Compression on Interlaminar Shear Strength of Polyimide/S2 Glass Laminate Insulators - Preliminary Report" H.Becker, T. Cookson (GDC) June 24 1985.

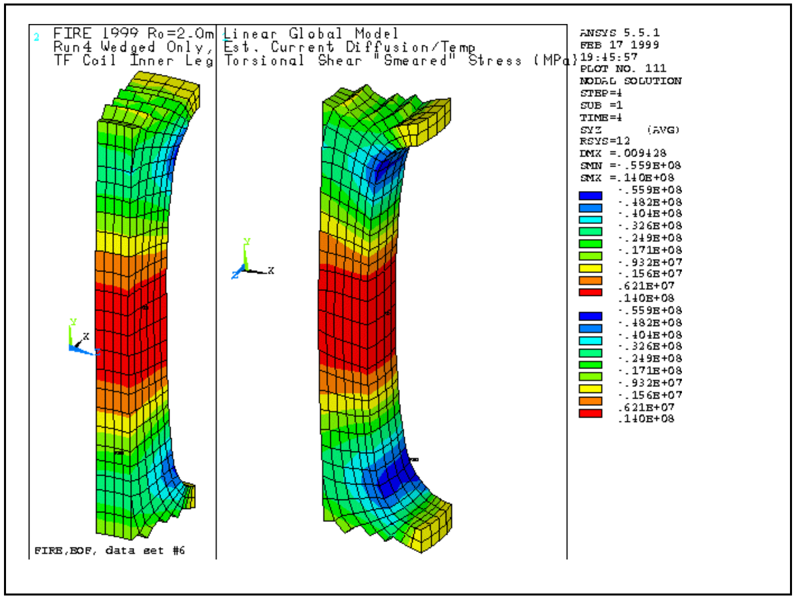
Insulating Material and Non-Metalic Strengths

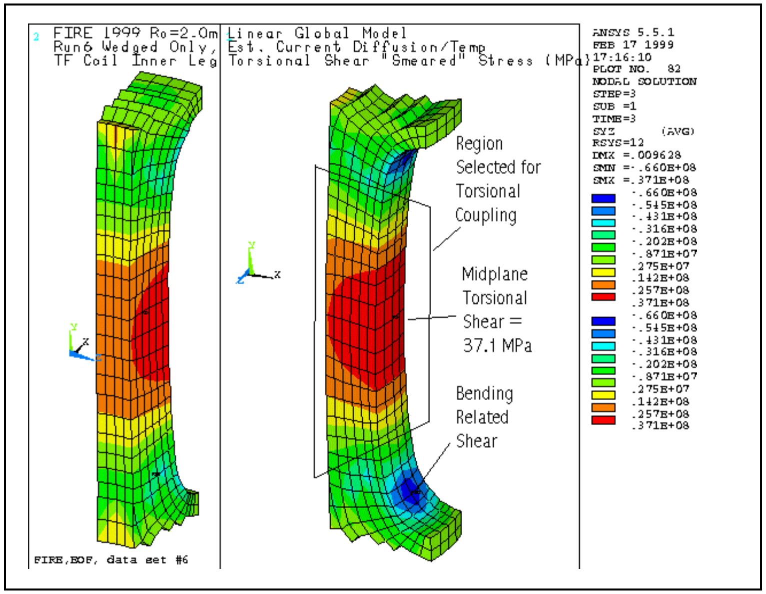
	MPa @4°K	MPa @77°K	MPa @292°K
Comp.Strength Normal to Fiber			
G-10CR	749(Ref 27)	693(Ref 27)	420 (Ref 27)
G-11CR	776(Ref 27)	799(Ref 27) 900(Ref 29)	461 (Ref 27)
CTD 101K AR irradiated	1260 (ave) (Ref 28)		
CTD-112P irradiated	1200 (ave) (Ref28)	1150(Ref 30 p 47)	
Polyimide/S2 Glass Laminate			1033 MPa, Ref [30]
Tensile Strength (Warp)			
G-10CR	862 (Ref 27)	825(Ref 27)	415 (Ref 27)
G-11CR	872(Ref 27)	827(Ref 27)	469 (Ref 27)
Tensile Strength (Fill)			
G-10CR	496(Ref 27)	459(Ref 27)	257 (Ref 27)
G-11CR	553(Ref 27)	580(Ref 27)	329(Ref 27)

The TF insulation needs to be thin. For FIRE's TF inner leg, 90% average packing fraction is assumed.

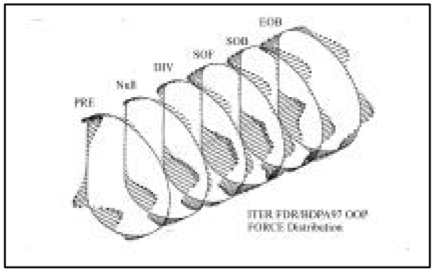
See The Separate Friction Handout for More Information on Low Friction Materials

OOP (Out-of-Plane) Analysis





Some Basics:

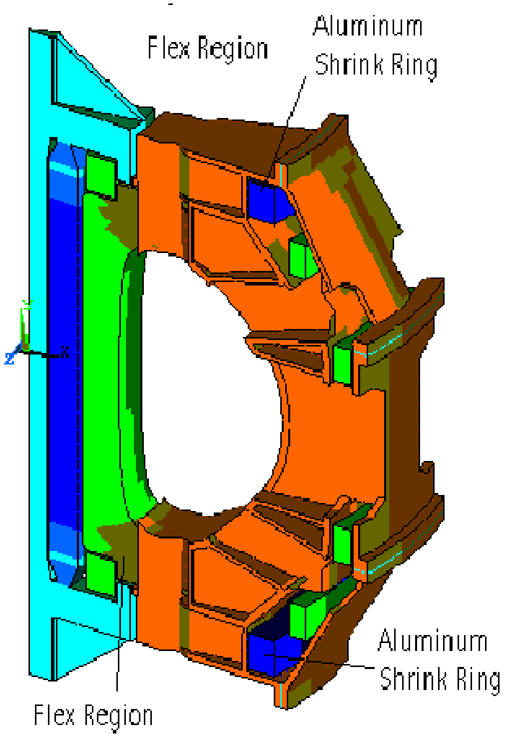


EOF TF Equatorial Plane Torsional Shear Stress - Comparison of Reactors

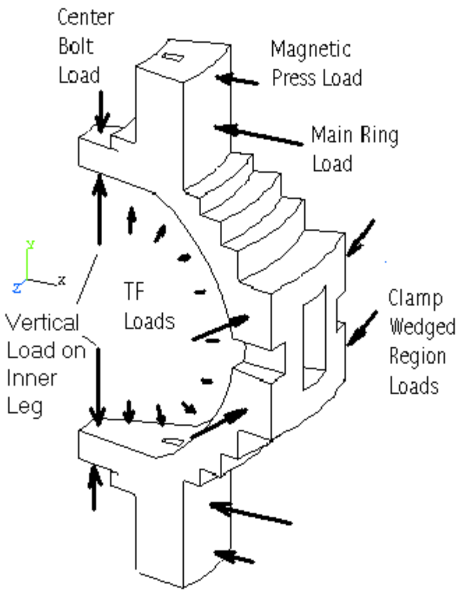
FIRE 10T, Wedged Inner Leg Torsionally Coupled R#4	**FIRE 12T, Wedged Inner Leg Torsionally Coupled R#42**	**FIRE 10T Wedged, Only Mid-Plane Torsional Coupling**	**BPXAT Rigid OOP Structure, Run#13**	**C-Mod Run #193**	**IGNITOR Run#4**
14.0	**19.9**	**37.1**	**35.9** **35.5** **(H.M.Fan)**	**22.8**	**33.3**

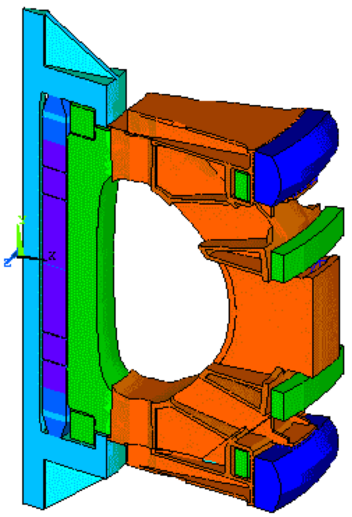
- Inner Leg Torsional Shear Distribution is a Function of Relative Stiffnesses of the TF and Outer Structures.
- OOP Forces are Worse with Segmented Solenoids and Highly Shaped Plasma's
- Friction at Wedge Faces Supports Torsional Shear. - Insulation Bond Does Not.
- Inner Leg Insulation System Does Not Need Bond Strength, Only Compression Related Shear Capacity -Important for Irradiated Insulation
- The Corners of the TF De-Wedge
- Corners Can Be Designed Not Support Torsion By Slipping, or Flexing - Slipping causes insulation Fretting. Flexing Makes the Inner Leg Sensitive to Net Torques during Faults.

FIRE Structural Ring Solves "De-Wedging" and TF Inner Corner Slippage.



The "Flex" Concept worked for Normal Loads, but a VDE, or PF Faults Could have Produced a Net Twist on the Central Column, Which the "Flex" Could Not Support"





FIRE with Radial Compression Rings, and Vertical Preload using a Tierod

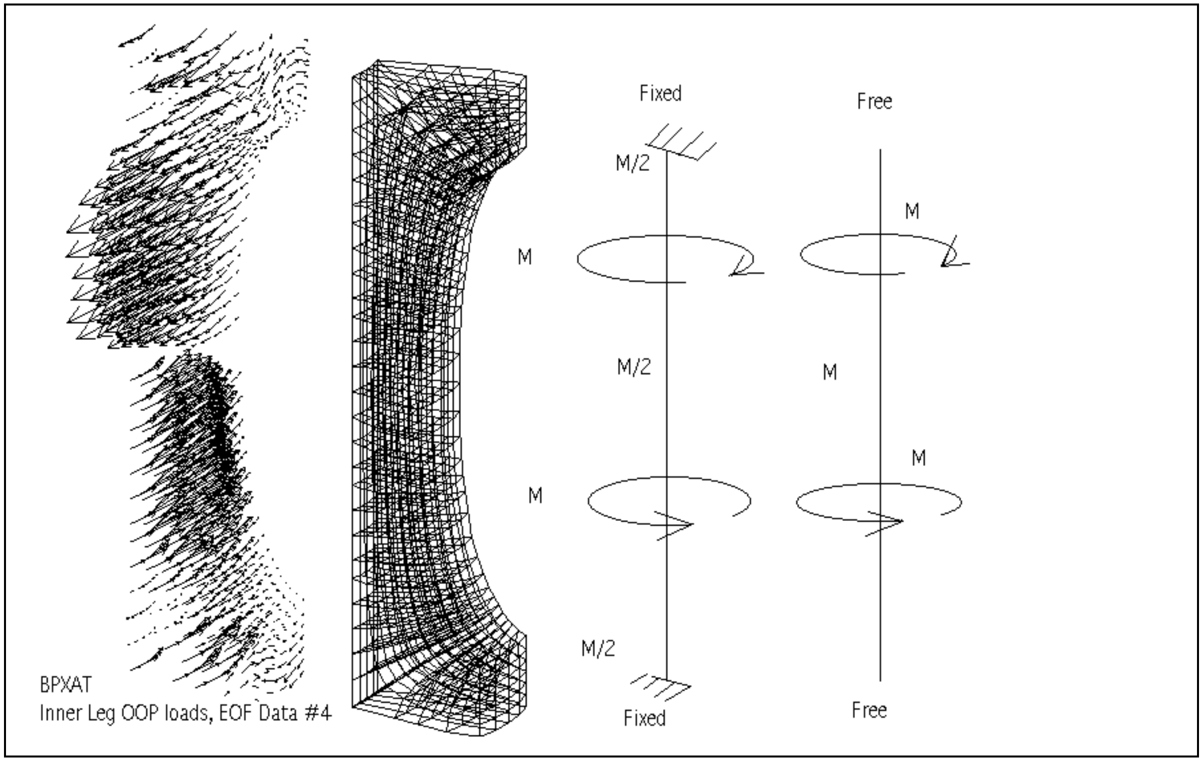
In IGNITOR the Main Ring and Mag. Press Overcome Radially Outward Loads and Cause a Vertical "Pinching" of the Inner Leg.

In FIRE, The Proposed Rings are Intended to Augment Wedging Pressures in the TF Inner Leg Corners to Help Support OOP Loads.

Clamp Function Can be Chosen based on Ring Vertical Position with Respect to the Horizontal Leg.

OOP (Out-of-Plane) Analysis

End Fixity of the TF Central Column Effects the Distribution of Inner Leg Shear



- The structural ring concept is intended to “force” the “fixed ended” shear distribution.
- Solutions which use the “free ended” shear distribution could be supported by mid plane wedge pressure, but the possibility of net torques and fretting failures at de-wedged ends argued for the “fixed ended” solution

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FIRE Fusion Ignition Research Experiment

Variation In Torsional Shear Results

Representative Distributions of Inner Leg Torsional Shear:

```
10 T Options ~30 Mid plane and ~50 ends
12 T Options ~40 Mid Plane and ~65 ends
```

There are many results for the torsional shear, There are over eleven scenarios Magnitudes are effected by Ip, TF field, bias, shaping, thermal distribution, external Structure Stiffness

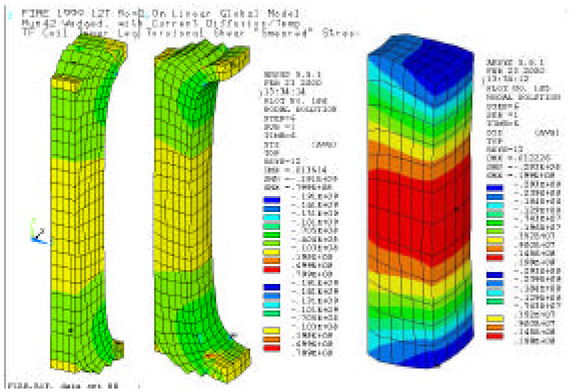
Torsional Shear and Shear Capacity (related to wedge pressure) scale as ~Bt^2 . Shear Margin is About the same for 10 and 12T Options.

Ring size and load can be adjusted to frictionally hold the corner. With the corner not slipping, and a friction coefficient which is the same as the Shear/Compression factor, The insulation is OK even if it doesn't have a bond strength.

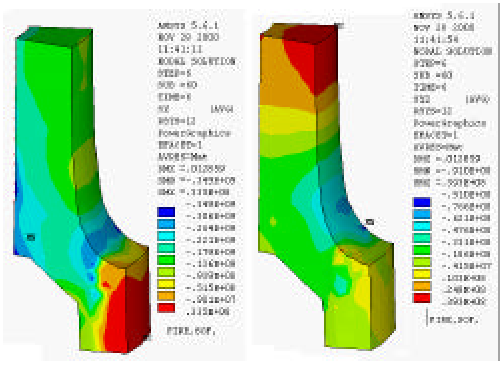
There are many runs with different friction coefficients, so there are many shear margin results. If there isn't enough corner compression, and the coil slips, The surface shear drops and the bending related shear goes up. If the wedge face insulation can take some fretting without failure, and the bending shear satisfies our allowable of $S_s = [2/3\ \tau_o] + [c_2 \times S_{c(n)}]$, **then this would also be OK too.**

The ring gives a lot of freedom in selecting insulation and surface friction for the corner of the TF.

The Bucked &Wedged arrangement trades wedge pressure sufficient wedge pressure to sustain shear.

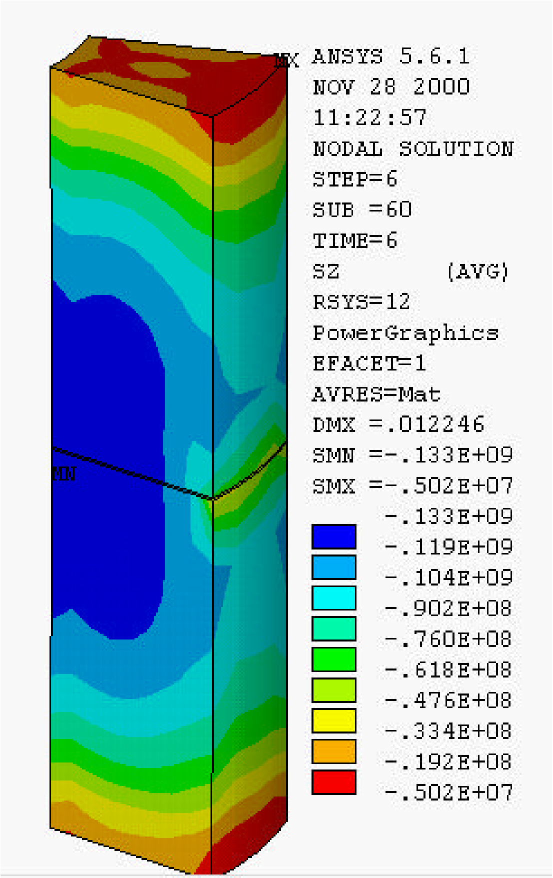


TF EOF Inner Leg Torsional Shear Stress - FIRE Run#42 with . 5m X .75m Compression Ring, Wedged With Tierod Removed

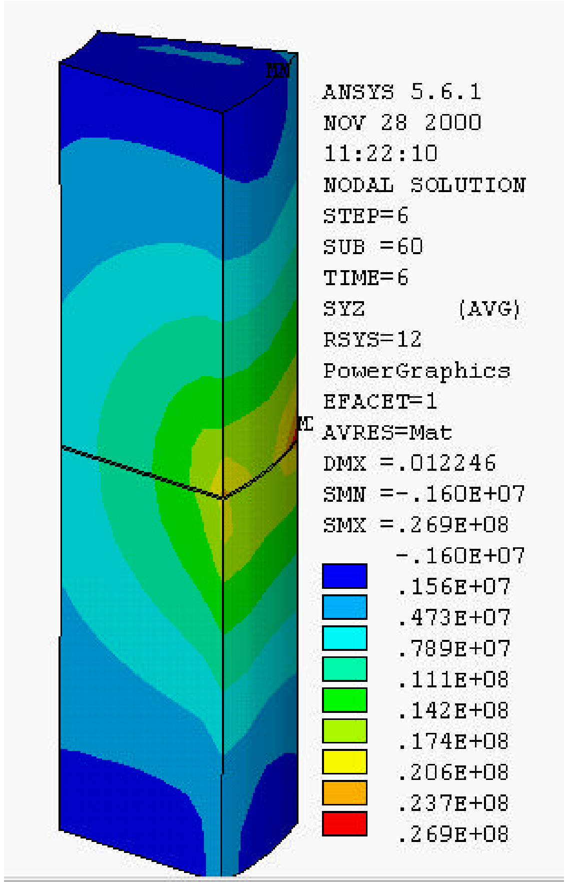


11.5T 7.7 MA Run #60 Bucked and Wedged SOF Torsional Shear Stress,Mu=.3 Toroidal Compression and Torsional Shear. Minimum Shear (Max Amplitude) occurs where there is about 200 MPa Compression

CS Torsional Shear



Run#60 Vertical Stress in CS1 -About -70 MPa at Mid-Plane OD



Run#60 SOF CS1 Torsional Shear -About 20 MPa at Mid-Plane OD

The Bucked and Wedged Solution Imposes Torsional Shear on the CS as well as the TF.

There is Adequate Vertical Compression to Support the Torsional Shear Imposed by the TF

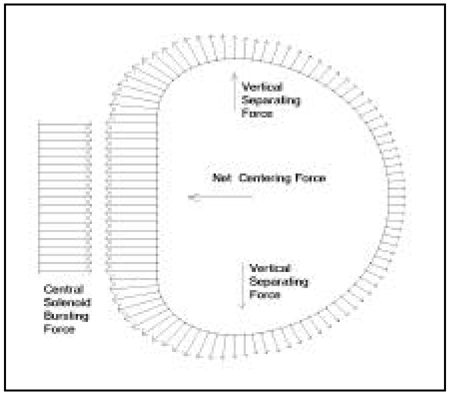
$$S_s = [2/3\ \tau_o] + [c2 \times S_c(n)]$$

With 70 MPa compression, and $c2 = .3$, τ_o could be zero

Bucked & Wedged -The Concept: What is the Advantage?

Ro=2.0 machines made of 68% BeCu

Structural Concept	Bo	TF stress (MPa)	Factor of Safety BeCu , Allowable =700 MPa
Wedged	12	700	1.0
Bucked and Wedged	12	326	**2.14**

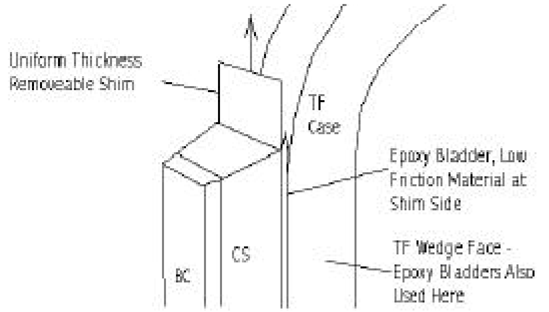


Bucked: TF Bears Against the Central Solenoid (JET, ITER FDR)
Wedged: (TF Inner Legs Support Centering Force as a "Vault", or "Wedged". - CS is Free-Standing, (BPX, C-Mod)
Bucked and Wedged: TF Bears Against the CS and is Wedged. Two Load Paths Effective for TF Centering Force (IGNITOR)

Fit-Up approaches, all will work:

CNC machine all mating surfaces to high tolerances, Face off Wedge face and Case with G-10 machining allowance layer in AES proposed fixture.Turn the CS to a known OD. Assemble TF array, put Ring preload on. Then machine the TF bore in place to CS OD, loosen ring, back off TF's slightly, insert CS and re-tighten TF's

Use epoxy bladder to fill CS/TF space at assembly (Use
CS Model coil type shim to release CS for disassembly) Use
Epoxy shims at TF wedge face



CS Model Coil Approach

Hire many 60 year old mechanics with blueing and scrapers to fit up the interfaces.

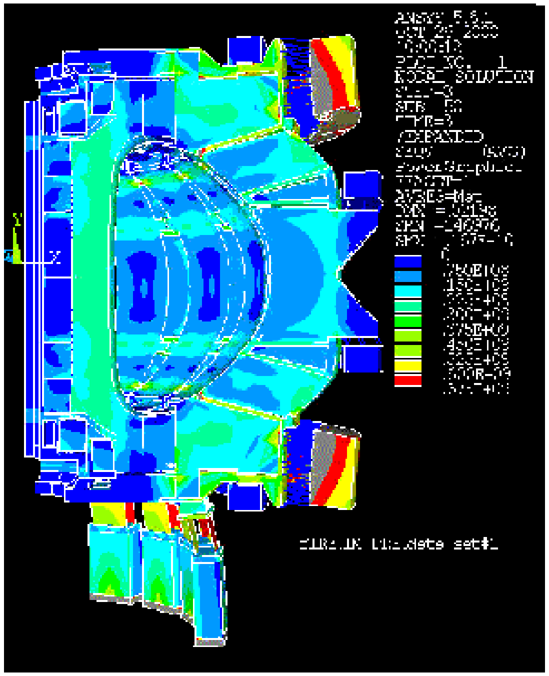
FIRE Bucked and Wedged
Ro=2.0 11.5T TF, 7.25 Ip , OFHC Copper Coils

- **From Elastic Analysis, Major Stresses In CS and TF Remain below 1.5 Sm for ranges in fit-up, Friction behavior, and preload. The Elastic-Plastic Analyses show the Limit Load to be Above 16T TF - Twice Operating Loads**

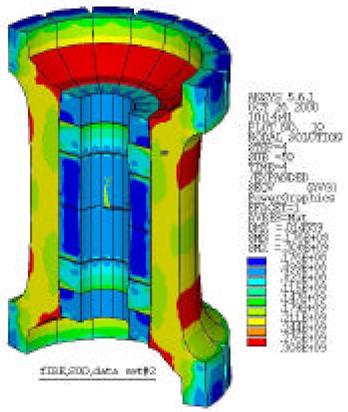
- **TF must bear on full height of CS.**
- **CS1 Heat-up causes bending in inner leg. Solution is to "preheat" CS2**
- **Bucking Cylinder is Needed to Demonstrate 16 Tesla Limit Load. 14cm thick Cylinder is Modeled, Lead Cut-Outs and Coolant Passages will require added build.**

OFHC 60%CW 1.5Sm (Based on lesser of 2/3 Sy or 1/2 Su)

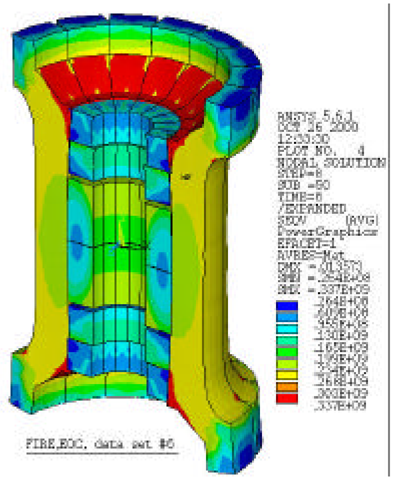
Temp=85 1.5Sm=347	Temp=176 1.5Sm=305	Temp=292 1.5Sm=262



Bucked and Wedged Model, Four Sector Symmetry Expansion, - Von Mises, Stress Contours " Notice Low Stress in CS and TF



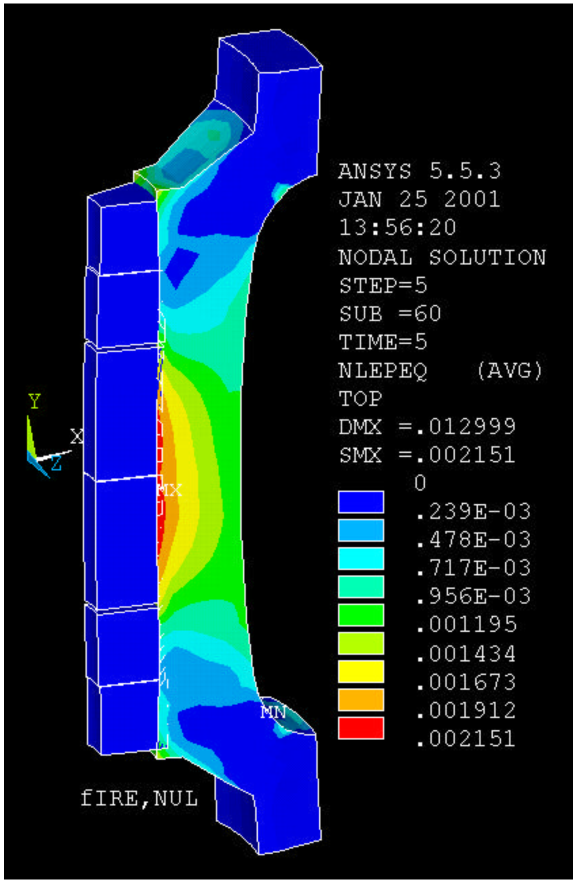
SOD R#57 Von Mises Stress, TF is Cold <176 deg K



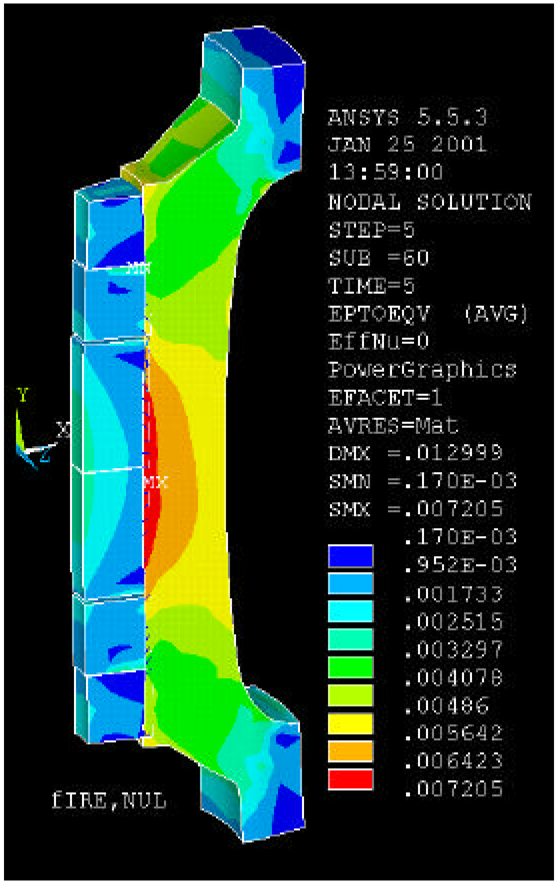
EOC Von Mises Stress, Mid Plane is Approaching RT

FIRE Fusion Ignition Research Experiment

FIRE Bucked and Wedged
Out-of-Tolerance Assembly, Run #68 2.5mm Gap Between TF and CS, 11.5T



Plastic Strain 2.5 mm gap between CS and TF 11.5T



Total Strain 2.5 mm gap between CS and TF 11.5T

FIRE "Worst Case B&W Fit-Up, 11.5 T, 2.5mm Gap" Insulation Stress= .007205*30 Gpa =216 MPa (Conservatively Assumes all Conductor Plastic Strain is in the Insulation Plane.)

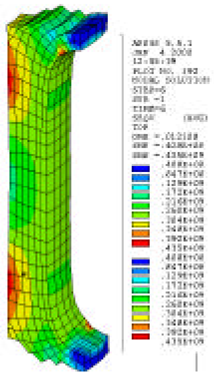
The Consequences of a Large Gap at Assembly are Benign.

FIRE Bucked and Wedged Analysis Run Summary

With Variations in Friction Coefficient CS/TF Gap, and Ring Load

Copper IACS=100%, Packing Fraction=.85 Sliding Gaps Everywhere, Mu as Noted, betaN = 2.0,TF End Temperature is 337K,δ=.8 (δ=.7R#57)

Run	Bt	Ip	Flat-top	CS/ TF Gap mm	Mu	CS2/CS3 Tstart	CS1 Peak Temp	Ring Load	TF E Limit MPa	CS E Limit MPa
74	16	7.6	21	.3	.3	120	275	1.0	270	216
73	15	7.6	21	.5	.3	120	275	1.0	270	216
72	14.0	7.6	21	.5	.5	120	275	1.0	270	216
70	11.5	7.6	21	-1.25	.3	120	275	1.0	270	216
69	11.5	7.6	21	1.25	.3	120	275	1.0	270	216
68	11.5	7.6	21	2.5	.3	120	275	1.0	270	216
65	12.0	7.6	21	.5	.3	120	275	1.0	270	216
64	11.5	7.6	21	.5	.3	120	275	1/4	270	216
63	11.5	7.6	21	.5	.25	120	275	1.0	270	216
62	11.5	7.6	21	.5	.3	120	275	1/2	270	216
61	11.5	7.6	21	.5	.2	120	275	1.0	270	216
60	11.5	7.6	21	.5	.3	120	275	1.0	270	216
57	11.5	7.25	21	.5	.3	100		1.0	270	No E-P
56	12	7.7	15	.5	.3	100		1.0	270	No E-P
49	11.5	7.7	15	.5		100		1.0	No E-P	No E-P



Effect of Bucking over Only CS1 From the Jan 2000 Presentation: Run#36 Bucked and Wedged,. EOF TF Inner Leg Von Mises

Run #56 PF coil currents from Kessel PF Flux Shifted 5V Packing Fraction=.85 (pfk7.inp)

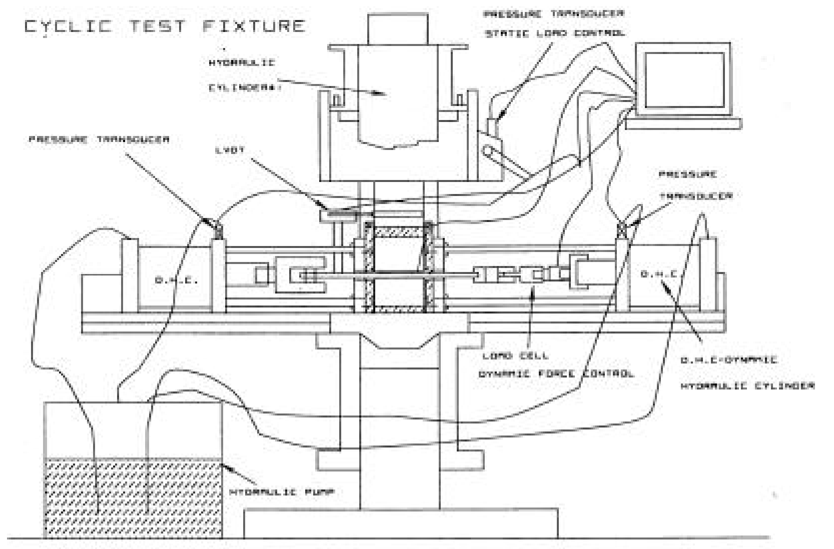
Run #57 PF coil currents from Kessel, 10-19-2000 Elastic-Plastic TF and CS
TF End Temperature is 337K

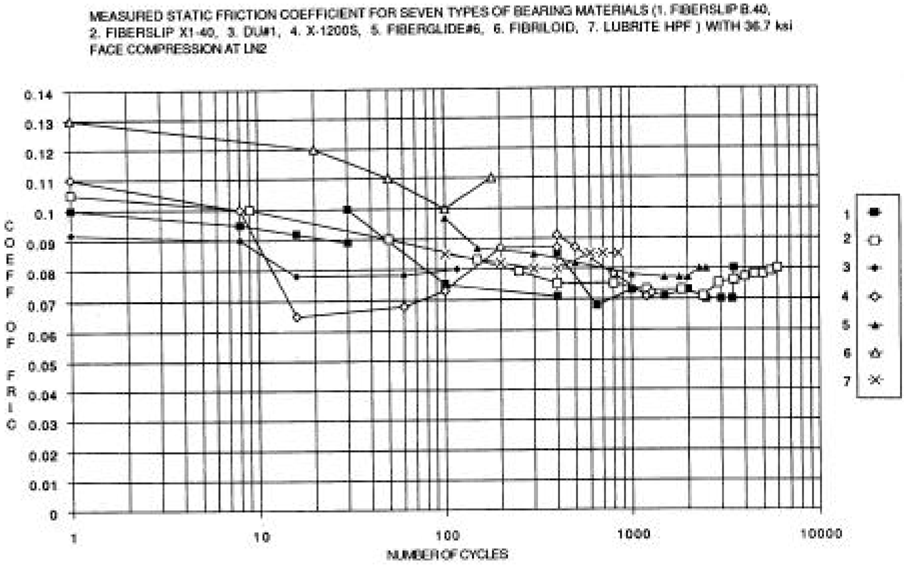
Run #60 PF coil currents from Kessel, 11-7-2000, Packing Fraction=.85 (pfk9.inp)
A NUL time point has been added. Stress levels are about the same as reported in the Oct. phone call. Peak TF Von Mises is 330 MPa, and TF plastic strains are below .4% Nul CS von Mises is 210 MPa and this is the worst through-out the shot including SOF in which the CS1 currents are -14.84 MA, up from -13.08 MA

FIRE Fusion Ignition Research Experiment

CS/TF Insulation/Low Friction Material Bucking Pressure Evaluation.
(See Also Separate Friction Hand-out)

Structural Concept	Run#	Bo	Ro	TF/CS Buck Pressure (MPa)	Factor of Safety ITER Qualification at -90 MPa Vacuum/4°K	Factor of Safety CIT Qualification at -253 MPa Cyclic 400 MPa Static N2Gas/80°K
Bucked and Wedged	74	16	2.0	-350	.257(dynamic)	1.14(Static), .7 (dynamic)
Bucked and Wedged	65	12	2.0	-141	.638	1.79
Bucked and Wedged 1.25mm stand-off	69	11.5	2.0	-80	1.125	3.16
Bucked and Wedged 1.25mm interference	70	11.5	2.0	-145	.62	1.74
Bucked and Wedged		10	2.0	-79.9	1.12	3.17


CYCLIC TEST FIXTURE


MEASURED STATIC FRICTION COEFFICIENT FOR SEVEN TYPES OF BEARING MATERIALS (1. FIBERSLIP B.40, 2. FIBERSLIP X1-40, 3. DU#1, 4. X-1200S, 5. FIBERGLIDE#6, 6. FIBRILOID, 7. LUBRITE HPF) WITH 36.7 ksi FACE COMPRESSION AT LN2

Bucked & Wedged: Effect of Gap or Interference at the CS/TF Interface

11.5T Bucked and Wedged Elastic-Plastic Results, NUL TF Inner Leg EQ. Plane(+/-.5m)

Run #	TF/CS Gap	Max VM	Max Tresca	SZ Wedge	SX Radial	SY Max	SY at Nose	εpvm	εpx (rad)	εpy (vert)	εpz (theta)
70	-1.25	255	290	-174	-154	175	45.3	0	0	0	0
61	.5	282	333	-252	-116	154	70.1	.00159	0	0	0
69	1.25			-279	-106	146	67.4	.00168	0.11e-3	.987e-3	-.912e-3
68	2.5			-303	-97.7	144	63.7	.003	.03e-2	.18e-2	-.

Starting with an interference (Negative Gap of -1.25mm), the gap between the CS and TF was varied up to 2.5mm.

11.5T Bucked and Wedged Elastic-Plastic Results, NUL CS EQ. Plane(+/-.5m)

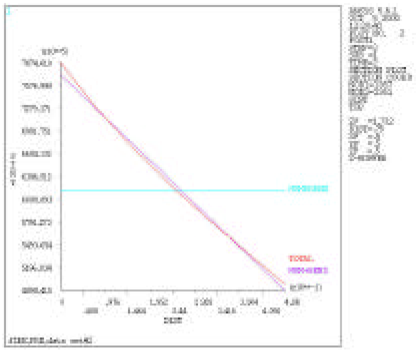
Run #	TF/CS Gap	Max VM	~Ave VM	Max Tresca	SX Radial	SY Max	SY at Nose	εpvm	εpx (rad)	εpy (vert)	εpz (theta)
70	-1.25	259						0	0	0	0
61	.5	225	166					.219e-3			
69	1.25										
68	2.5										

Satisfying the Primary Membrane Stress Criteria For the Ro=2.0m Wedged Configuration:

- **What is the Primary Load Path for the Centering Load? ---Only Wedging.**
- **What is the Primary Load Path for the Vertical Load? Both Inner and Outer Legs? Just the Outer Structure?**
- ***Qualification Approach: Use Hand Calculations Backed-Up by FEM Analysis - Show that the Outboard Structures Can Take the Vertical Load, and Inner Leg Takes the Centering Load by Wedging. Criteria Document I-3.1.1***

Inner Leg Stress Summary

Stress Component	10T	12T
Primary Membrane Allowable	480MPa	480MPa
Primary Stress With Vertical (Hand Calculations)	400MPa	576MPa
Primary Stress Without Vertical	249MPa	358MPa
Equatorial Plane average Wedge Pressure at Precharge - FE results, run#52		397 MPa
Equatorial Plane average Wedge Pressure at EOF - FE results, run#52		400 MPa



Results of Linearizing the TF Inner Leg Stress (ANSYS PLSECT command) applied to a path across the radial build of the inner leg of the TF - Vertical loading included. -ANSYS Results With Vertical Stress

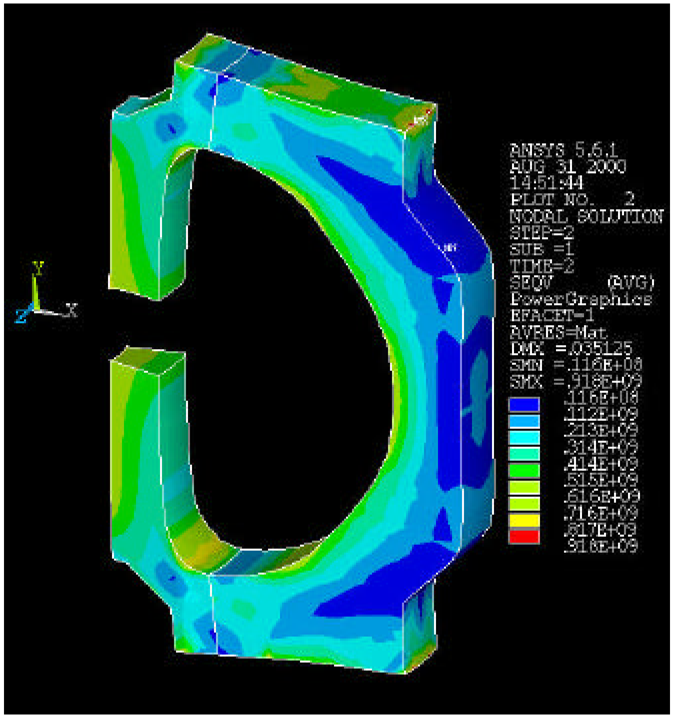
Loading	Load Step	Equiv Stress Type	Peak	Membrane	Membrane +bend
Allowable Stress				480	728
Precharge	2	Tresca	787.4	618.8	769.6
Precharge	2	VonMises	689.4	540.2	671.8
EOF	6	Tresca	698.5	577.9	680.3
EOF	6	VonMises	627.0	505.0	604.0

The Difference between EOF and PRE is the Result of a Thermal Component.

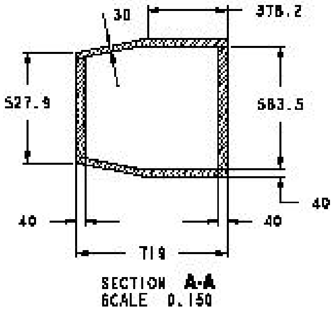
For the Inner Leg Primary Stress to be Only the Wedge Stress, The Outer Leg and Case Must Take All the Vertical Load

Outer Leg Conductor Stress Summary

Stress Component	10T	12T
Allowable	233MPa	233 MPa
Primary Stress With 100% Vertical	207MPa	298 MPa
Primary Stress With 200 MPa (at 10T) Contribution from the Case	155MPa	223MPa (But this requires 300 MPa Sm for the case



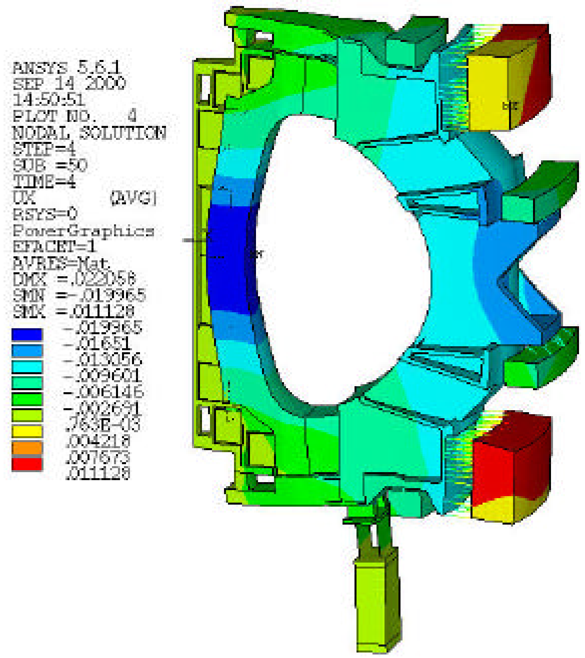
Coil Von Mises Stress. The outboard leg mean stress, Run #54



Case Cross Section from the Drawings, May 2000. The Area is .030*2*.719+.040*(583.5+527.9)=.0876m^2

See:
"FUSION IGNITION RESEARCH EXPERIMENT (FIRE) MAGNET SYSTEM STRUCTURAL ANALYSES", ANS Topical On the Technology of Fusion Energy for a Complete Discussion of the Primary Stress Evaluation for the Wedged 12 T BeCu Confiuguration

Wedged TF Coil Elastic - Plastic Analysis to Demonstrate "Adequate Ductility"



Wedged Only, 14T Overload, Radial Displacement

Design Criteria Document Requires "Adequate Ductility" How do we Define and Evaluate This?

At 14T over-load, the Wedged Concept has only 1.8% Total Strain, Well Below the 14% Elongation for the 68% IACS BeCu

Radial displacements of the Inner Leg of the Wedged Machine with a 14 T TF loading is 1.9cm including the thermal contraction. The 12T elastic result is 5 mm.

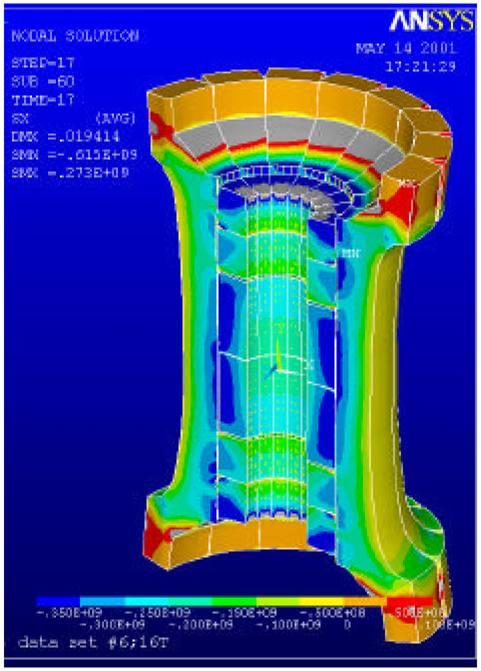
FIRE Magnet Concept	**TF Material Elastic Limit**	**Total Elastic +Plastic VM Strain**	**Location**	**Insulation Stress at E_{ins}=30 Gpa**
Wedged Only/BeCu 13T	**600 Mpa**	**.0067**	**Mid-Plane**	**197 MPa**
Wedged Only/BeCu 14T	**600 MPa**	**1.83%**	**Mid Plane**	**549 MPa***

***449 MPa if Only In-Plane Strains are Considered**

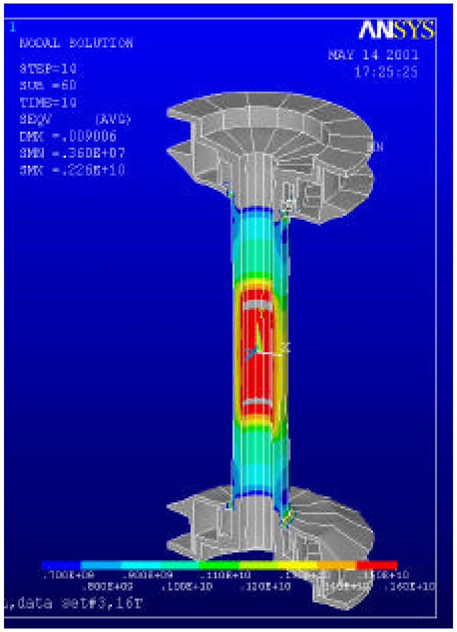
FIRE Fusion Ignition Research Experiment

Satisfying the Primary Membrane Stress Criteria For the Ro=2.0m Bucked and Wedged Configuration:

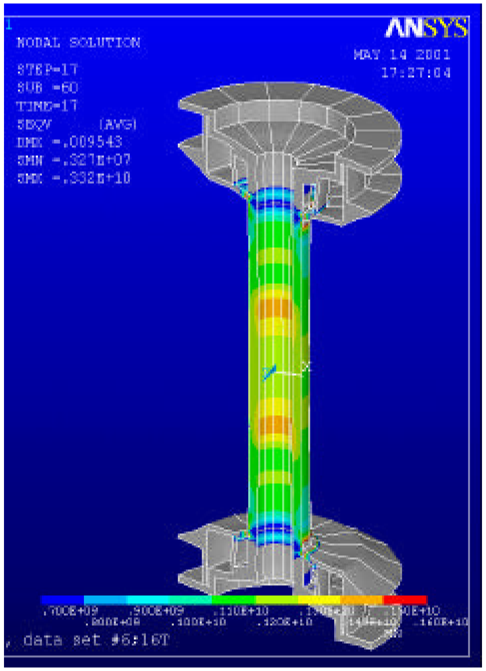
- **What is the Primary load for the Inner Leg? - Centering Load or Vertical Load? Both?**
- **What is the Primary Load Path for the Centering Load? Bucking? Or Wedging?**
- **What is the Primary Load Path for the Vertical Load? Both Inner and Outer Legs? Just the Outer Structure?**
- ***Qualification Approach: Use Elastic-Plastic Analysis or Limit Analysis at Twice the Normal Load. Criteria Document I-3.1.1 - To Qualify the Design for 11.5T TF Field, Analyze to 16.3T***



Radial Pressure Peaks at about -350 a 14cm Bucking Cylinder is Used at CS ID



Bucking Cyl Stress Peaks at NUL at about 1600 MPa., Which is the Ultimate for 50% CW 304 SST

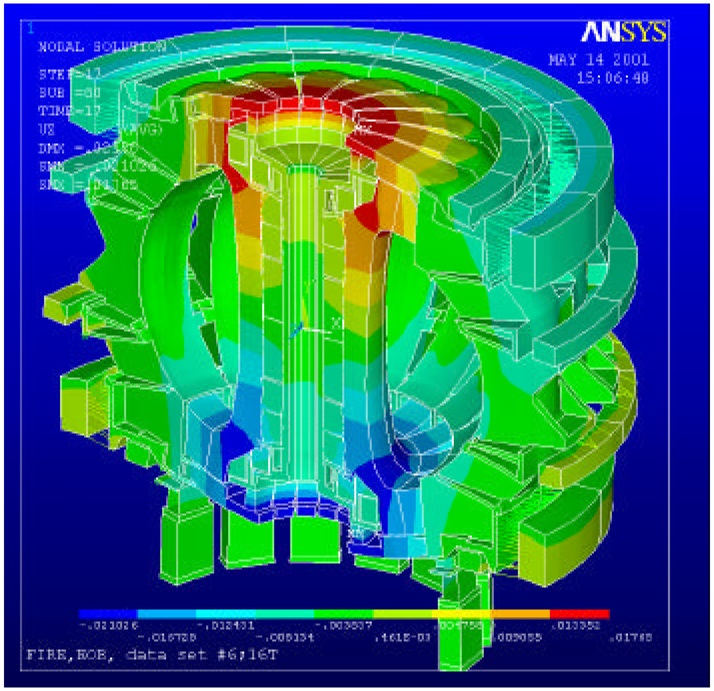


Bucking Cyl Stress is Lower at EOB due to the CS being energized.

Bucked & Wedged 16T TF Elastic-Plastic Limit Load Analysis

Solution is Bounded, Stable and Converged Throughout Two Shots.

The Bucked and Wedged Configuration Could Survive a 16T Loading

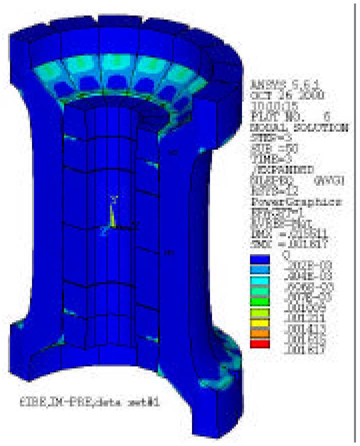


Bucked and Wedged 16T Limit Analysis, EOB Vertical Displacements, Including Cool-down

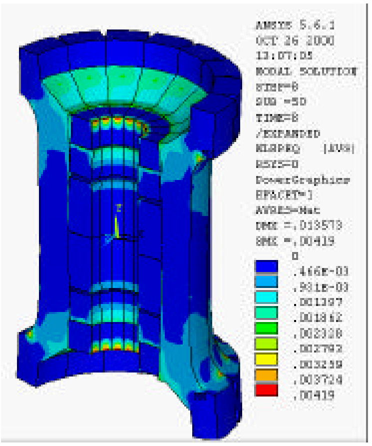
Bo	11.5	14	15	16
Run			73	74
BC VM			1270	1600
BC Hoop			-836	-1130
BC vert			639	
TF VM				
TF εp VM			.008	.0142
TF Hoop			-325	
TF Vert			+277	+346 (plasma side)
CS Von Mises			284	320
CS Hoop			-300	-307
CS εp VM			.006	.02
Case VM				
Case UY Max			+.0002	.007
Case UY Min			-.013	-.016

Further Discussion of the Bucked and Wedged Limit Load Analysis in On the Web including an Animation that shows the Global Displacements of the Machine Along with the Central Column Plastic Strain

TF Arch Region Stresses (Both Wedged and Bucked and Wedged)



11.5 T Precharge Equivalent Plastic Strains



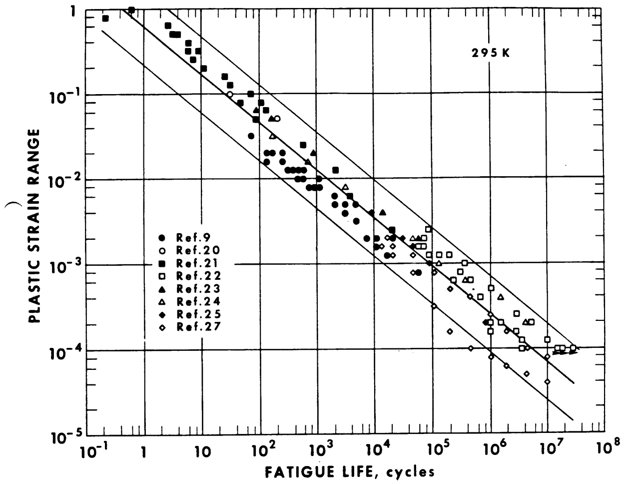
11.5 T EOC Equivalent Plastic Strains

Strain Controlled Low Cycle Fatigue in the "Arch" Region

12 T strain Results. - Look at Cyclic Principal Total (Elastic+Plastic) Strains

The Strain Range is about .4%, which give you about 20,000 cycles , or about 1000 cycles with a factor of 20 on life

Total Principal Strain Com-ponent	Pre-load	EOF	Hot-No-Load	Cold No Load
EPTO1	.0016	.003	.004	.003
EPTO2	~0	-.001	-.001	~0
EPTO3	-.0035	-.007	-.00733	-.0051



C10100-C10200 Copper (Annealed, Cold Worked) Nist, Reed & Simon [16]

Insulation Strains and Stresses Imposed by Total or Elastic + Plastic Strains
Bucked and Wedged vs. Wedged

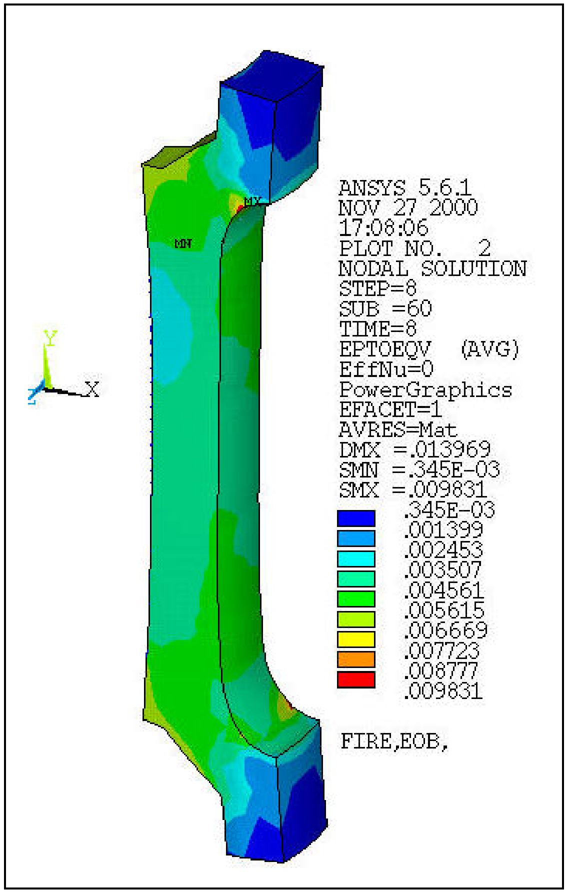
TF Coil Plastic Strain and Insulation Stresses
(Conservatively Assumes all Conductor Plastic Strain is in the Insulation Plane.)

FIRE Magnet Concept	Peak Field	TF Material Yield	Total Elastic +Plastic VM Strain	Location	Insulation Stress at E_{ins}=30 Gpa
Bucked and Wedged /OFHC	**12 T**	**350 MPa**	**.0098**	**Arch**	**294 MPa**
Wedged Only /BeCu	**13 T**	**600 MPa**	**.00657**	**Mid Plane**	**197 MPa**
Wedged Only/BeCu	**14 T**	**600 MPa**	**.0183**	**Mid Plane**	**549MPa***

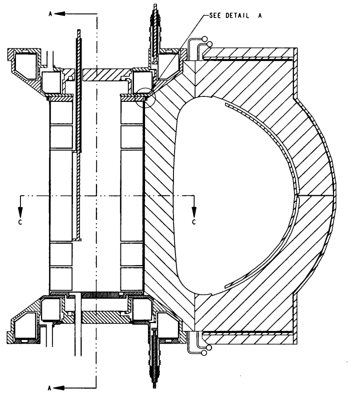
***449 MPa if Only In-Plane Strains are Considered**

Insulating Material Strengths, MPa

	@4	@77	@292
Comp.Strength Normal to Fiber G-10CR	749	693	420
Comp.Strength Normal to Fiber G-11CR	776	799	461
Tensile Strength (Warp) G-10CR	862	825	415
Tensile Strength (Warp) G-11CR	872	827	469
Tensile Strength (Fill)G-10CR	496	459	257
Tensile Strength (Fill) G-11CR	553	580	329

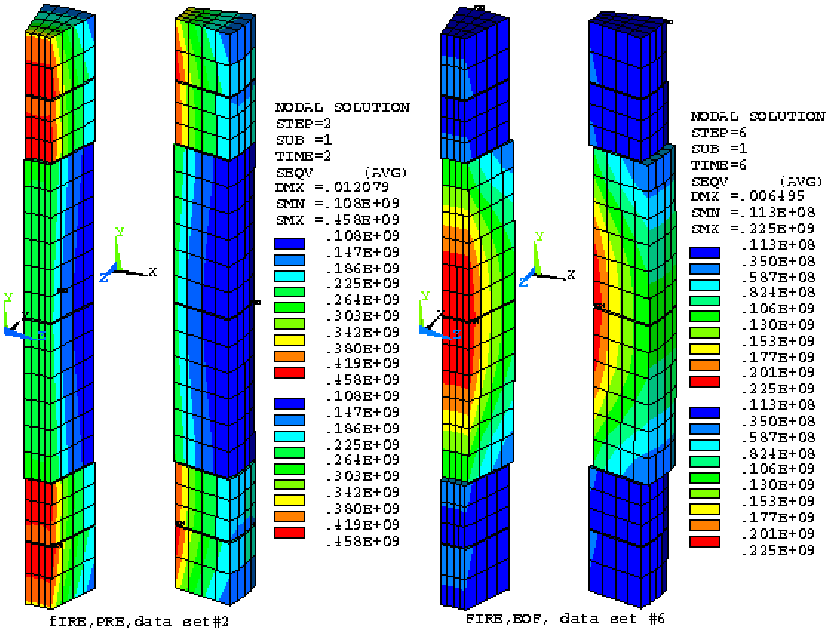


Basic Characteristics of the FIRE CS and PF Coil System



Central Solenoid Section with one TF Coil

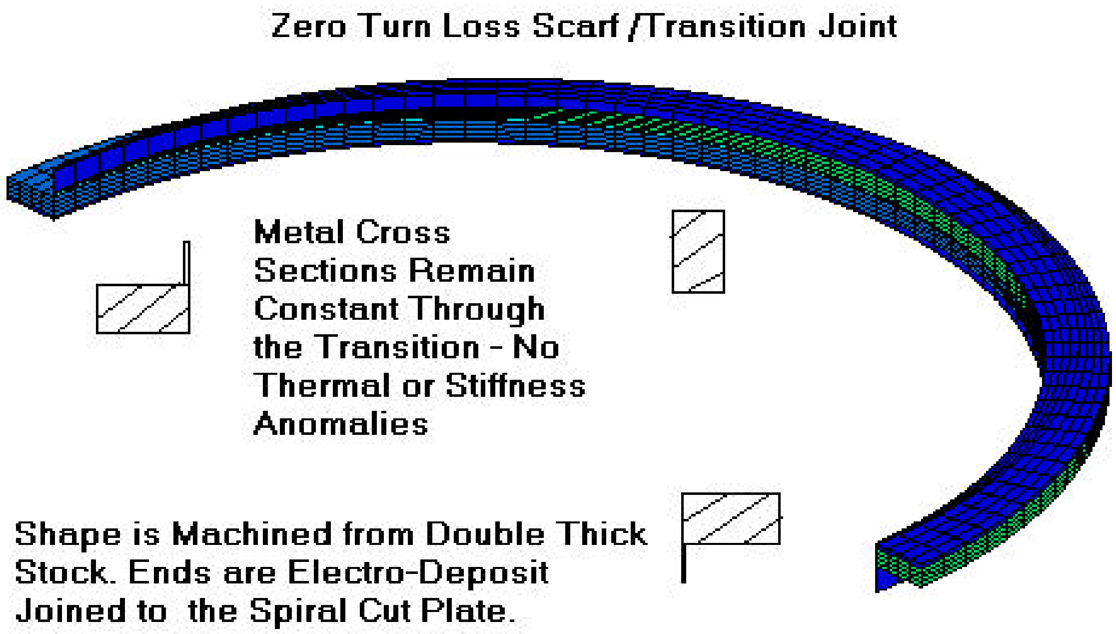
- **OFHC Copper Segmented Solenoid and PF coils**
- **Base design is free standing, Bucked and wedged is carried as an option**
- **Solenoid uses water-jet plate double pancake winding. Uses a constant cross section, zero turn loss inner joint.**
- **PF coils are Strip wound Plate**



CS Von Mises Stress - Smeared

CS Inner Joint

- Reactor Sizing needs to include allowance for the local details of the coil design.
- Multipliers are applied to account for insulation, cooling and joint details.
- Goal: No Multiplier due to joint details.



Zero Turn Loss Scarf /Transition Joint

Metal Cross Sections Remain Constant Through the Transition - No Thermal or Stiffness Anomalies

Shape is Machined from Double Thick Stock. Ends are Electro-Deposit Joined to the Spiral Cut Plate.

Inner Joint for Pancake Wound Coils

- No Stress or Stiffness anomaly - Working Stress is the Same as for the Winding.
- No Thermal Anomaly in Normal Conductor Coils - No Differential Thermal Strains
- No Turn Loss
- No Projection into the Bore

Used with more Conventional Outer Joint for Ease of Insulation and Assembly of Double Pancakes

Maintenance of Concentricity In the Segmented CS

Bucked And Wedged

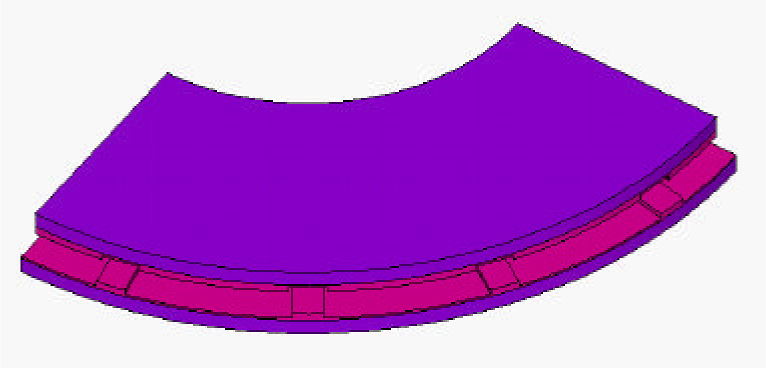
Radial Groove Detail May Not Be Needed, Or At Least Radial Motion Will Not Occur Under Load

CS is Clamped Between TF and Bucking Cylinder.

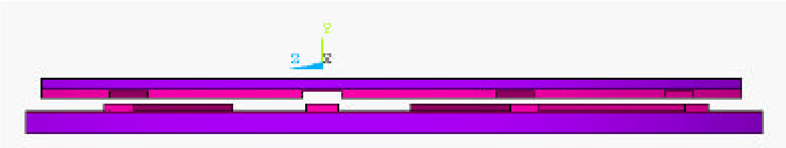
Differential Radial Motion Only Occurs When TF is Turned Off.

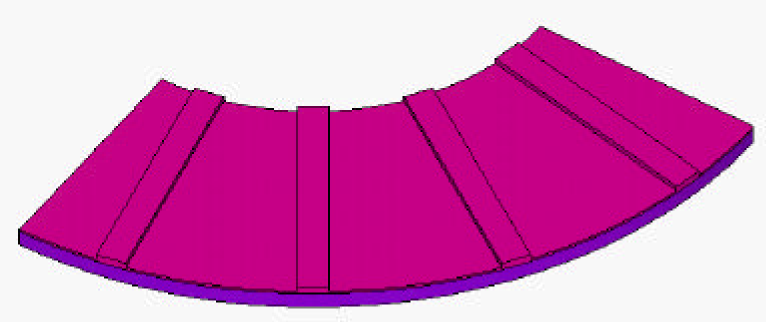
Lead Support Motion Does Not Occur Under Load

Wedged



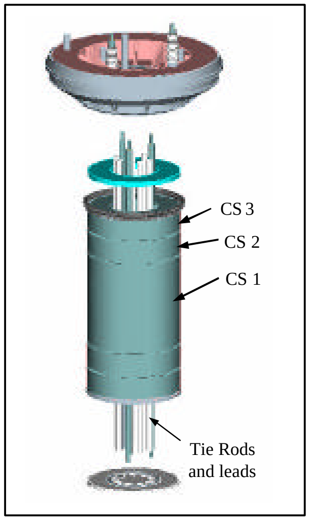
Low Friction Surface, Radial Grooved Plates Between CS Segments - Allow Differential Radial Motion due to Thermal and Lorentz Force Differences. Lead Support Must Allow Radial Motion Under Load as Well.

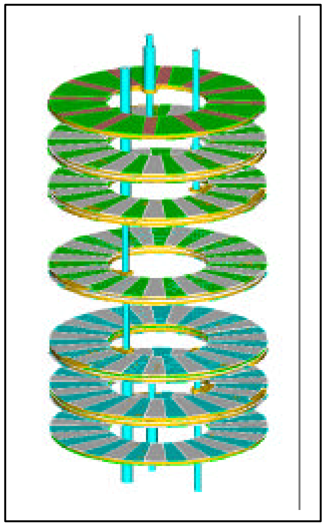




CS Inner Leads

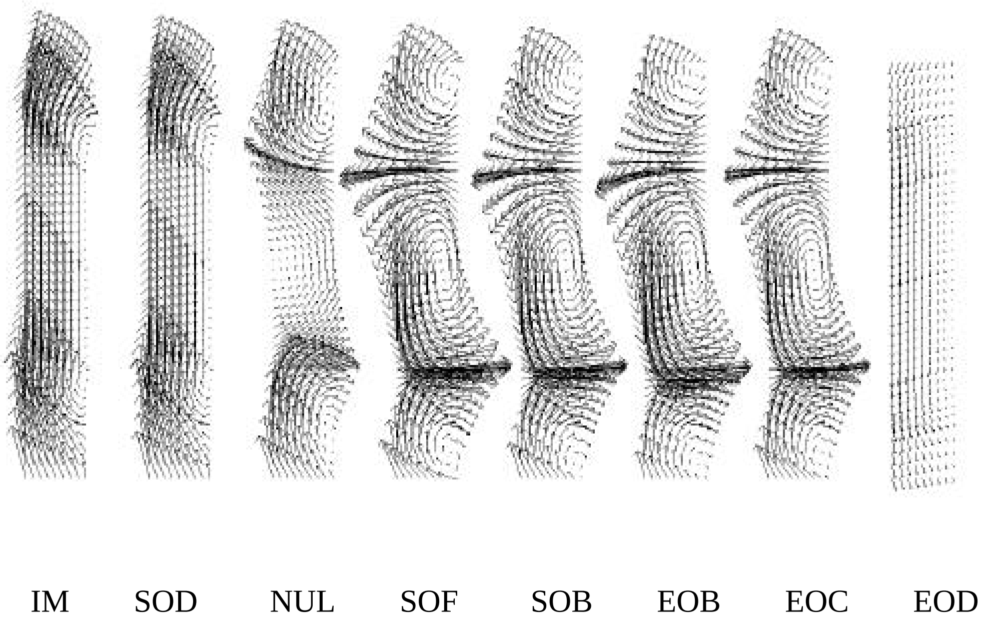
Inner Leads Have No Multiplier As Well - It will be Tough Because of the Radial Field in the Bore





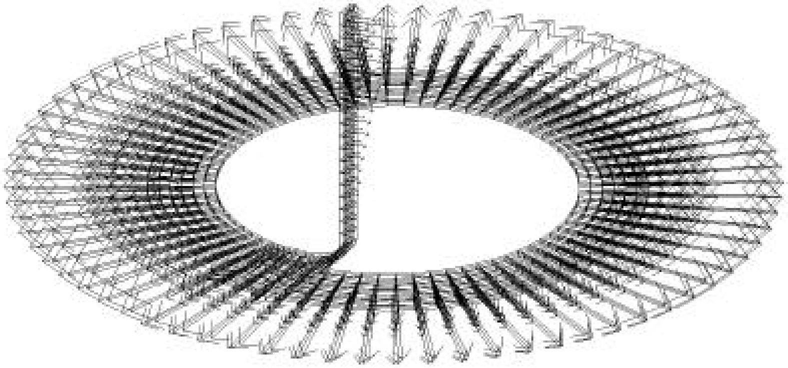
Max Fields in the CS Bore, Kessel Scenario #11, Buc9 fields,

Time Point	Br max	Bvert max	Btot max
IM	2.550120	18.20790	18.21001
SOD	2.314950	16.50390	16.50589
NUL	4.955180	12.26410	12.27314
SOF	9.462240	10.33470	15.66222
SOB	8.258770	9.144980	14.15456
EOB	8.311100	6.767660	16.42905
EOC	7.541010	8.863180	11.96668
EOD	0.5575220	0.000E+000	4.126797

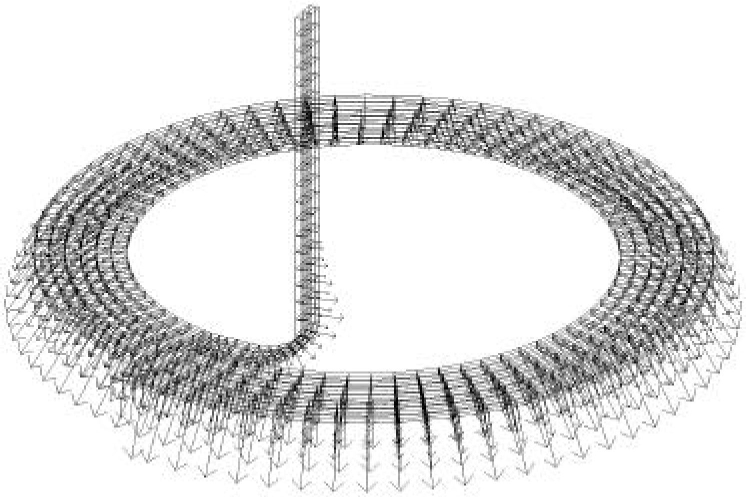


Field Vectors in the FIRE Central Solenoid, showing large radial fields that will cross the leads as they run up the bore. Kessel Scenario #9, Buc9

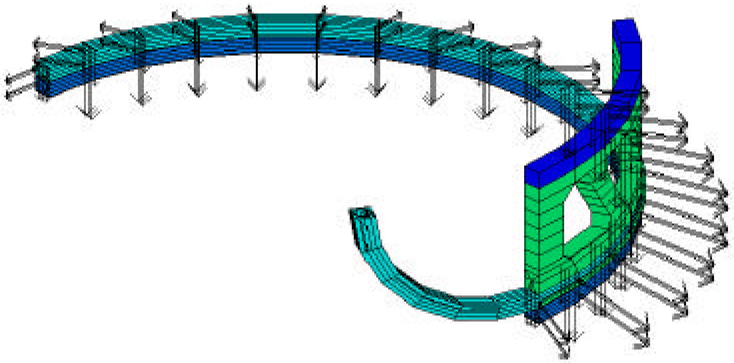
One Possible Solution:
Use CS Model Coil Lead Concept, That was Mostly Restrained By Friction.



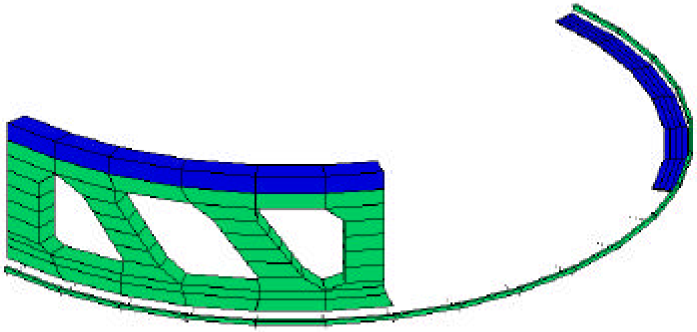
Break-out positioned at equatorial plane



Break-out positioned at elevation of CS1 to CS2 interface - EOB Coil Currents from Scenario #11 where CS1 has -14.86MAT and CS2 has +3.960MAT. In just the "Up-Turn" + Vertical Run, the net Vertical Force is 83130N or 18,700 Lbs, downward.

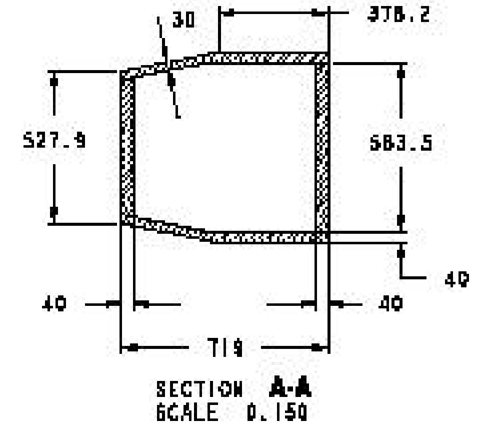


CS Model Coil Lead FE Model updated with better modeling of the shear panel, and smaller extent of de-bond



Shear Panel Supports Some Tension, But Friction Support Most of the Hoop Tension.

TF Leads



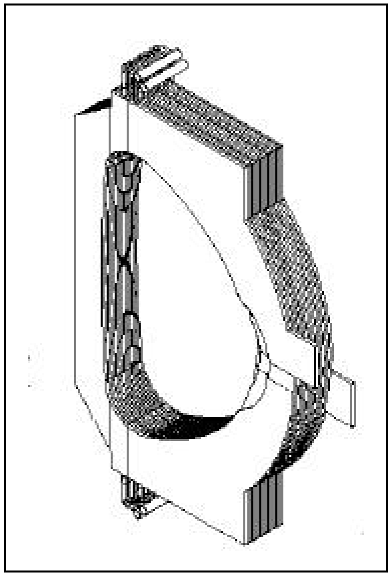
Case Cross Section from the Drawings, May 2000. The Nominal Outboard Leg Conduction Area is .719+.583.5=.419m^2

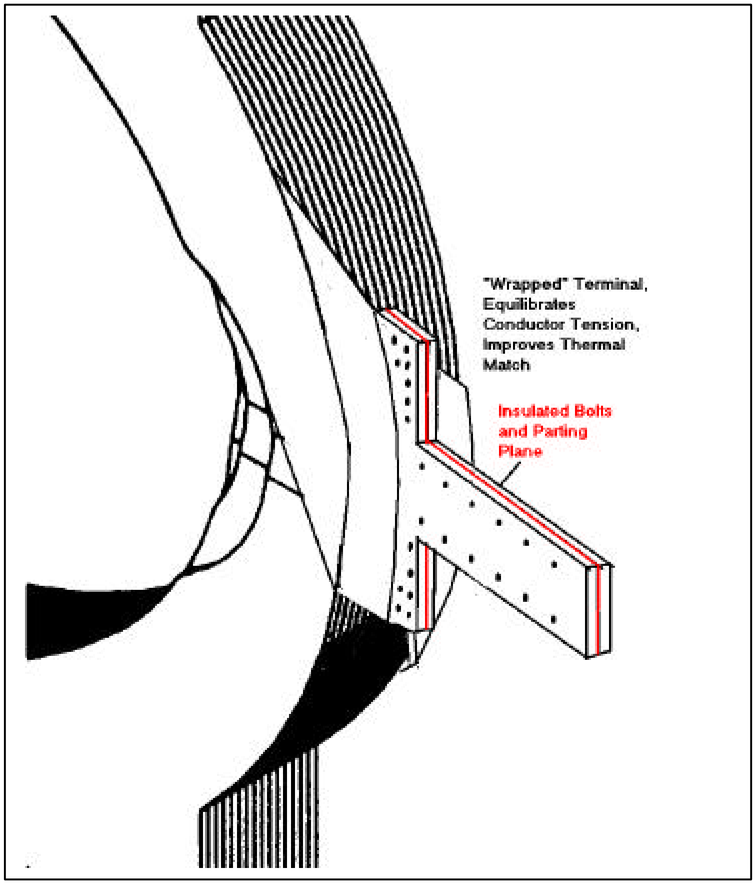
Present Terminal Configuration:

- **"Cut-Out" Increases Temperature from 160°K to 300 °K**
- **Tension inTF Turn Is Not Reacted**

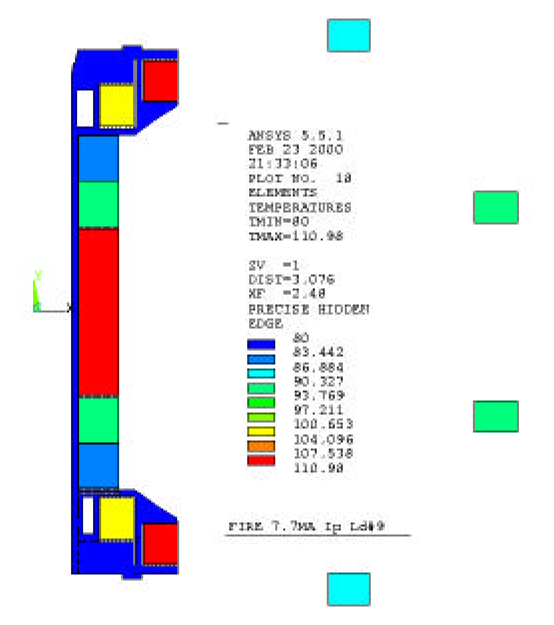
Proposed "Wrapped" Configuration:

- **Conduction Cross Section Matches Interior Turns**
- **TF Tension is Equilibrated**





CS/PF Temperature Summary



FIRE* CS and PF coil Temperatures, 15 second 10T TF, 7.7 MA
Copper IACS=100%, Packing Fraction=.85 (pft1.inp)

Time (sec)	CS1	CS2	CS3	PF1	PF2	PF3	PF4
5	84.4862	84.5903	82.3161	84.5120	84.5120	80.0266	80.0115
5.01	84.5092	84.6139	82.3280	84.5351	84.5351	80.0268	80.0116
12	89.7898	93.0775	88.0673	98.9259	98.9259	80.3592	84.1035
14.5	94.6423	94.0828	89.0958	106.397	106.397	81.1031	88.1192
32	133.203	96.0205	91.1334	190.949	190.949	89.4062	116.937
35	140.532	96.7718	91.9346	204.018	204.018	89.9582	121.641
39	143.667	97.2025	92.4003	206.680	206.528	89.9943	123.210

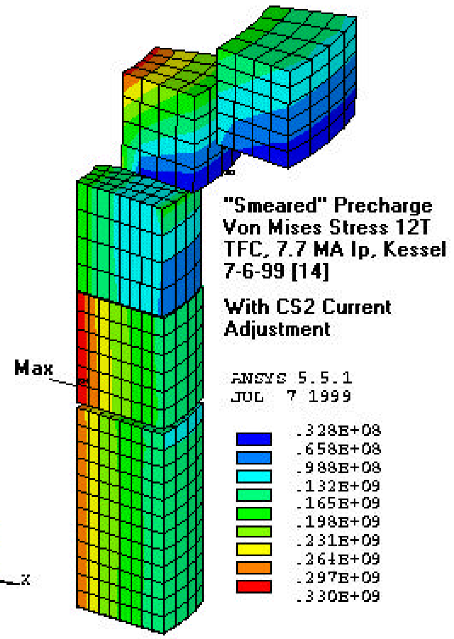
Temperatures based on PF coil currents from Kessel, 10-19-2000, for the Bt=11.5 T case. Parameters to note...---> Ip = 7.25 MA---> betaN = 2.0---> flattop time = 21 s Copper IACS=100%, Packing Fraction=.85 (pfk8.inp)

Time (sec)	CS1	CS2	CS3	PF1	PF2	PF3	PF4
0	80	80	80	80	80		
0.01	80.0125	100.022	100.01	80.0188	80.035	80.02	80.02
7.0	96.6269	128.899	107.01	88.26	101.37	80.35	80.07
9.5	99.002	135.874	109.693	93.079	108.305	80.705	82.039
28.0	165.101	159.766	127.93	162.85	192.32	88.36	126.6
31.0	181.14	162.163	129.79	179.791	212.78	89.59	136.94
35.0	200.96	166.28	133.28	200.9	238.13	91.615	146.44

CS Stress Summary

Wedged Design, Results of Weighted Scenarios 12 T 7.7 MA scenarios, Packing fraction=.85 Estimated Bias Needs More Work

Weight New - shifted, flux, state, everywhere, back by,5,V with CS2 Precharge adjustment	Weight Old 12 T 7.7 MA scenario	PRE	EOB
3/4	1/4	CS2 PRE VM=354 Temp=85 1.5Sm=347 F.S.=.98	CS1 EOB VM=332 Temp=176 1.5Sm=305 F.S.=.92

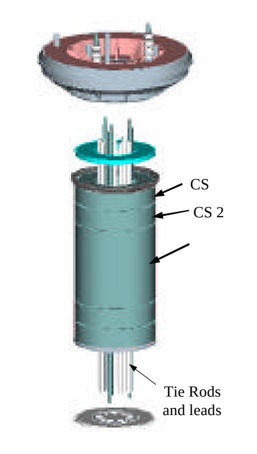


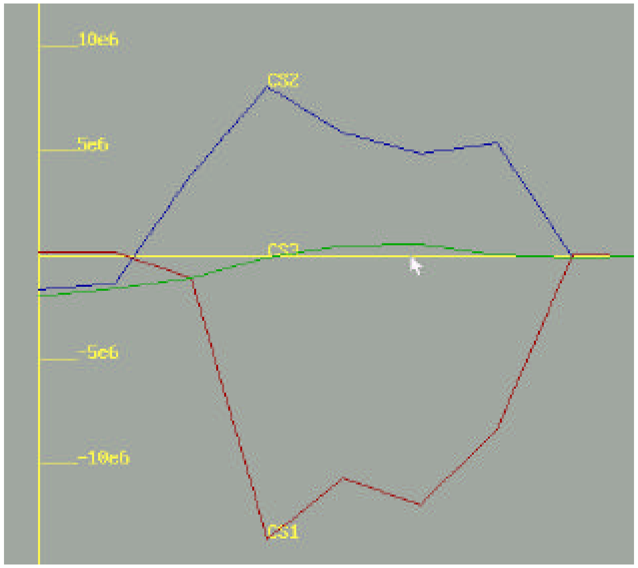
"Smeared" Precharge Von Mises Stress 12T TFC, 7.7 MA Ip, Kessel 7-6-99 [14]

With CS2 Current Adjustment

	FIRE-10T(12T)		FIRE*	
Ro	2.0 W	2.0 B&W	2.14 W	2.14 B&W
CS Peak Stress at PRE	294(354)	(228[1])	322(322)	(228[1])
CS Temp at PRE	83(85)	83(85)	88?(88)	88(88)
CS allowable at Pre[1]	345(347)	345(347)	344(344)	344(344)
F.S at Pre	1.15(.98)	2.1(1.5)	1.07(1.07)	2.1(1.5)
CS Peak Stress at EOB	182(332)	(30)	190(279)	(30)
CS Peak Temp (EOB)	159 (176)	159 (176)	177(227)	177(227)
CS Allowable (EOB)	313(305)	313(305)	304(280)	304(280)
F.S at EOB	1.7(.92)	>10(10)	1.6(1.0)	>9(9)

CS Tierod or Inner Shell Vertical Loading





CS Segment Vertical Force Summation per 1/16 sector, Chuck

CS 3 contributes little to the launching load. CS2 develops about 8 MN vertical load

The area of 1/16 sector of the mandrel shell is 3.72e-3 m^2.

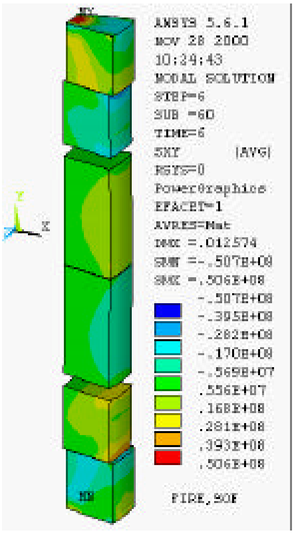
It is 5 cm thick

If the Mandrel Shell takes all the loading, the tensile stress 8e6/3.72e-3=2150 MPa

But the Model only shows about 700 MPa

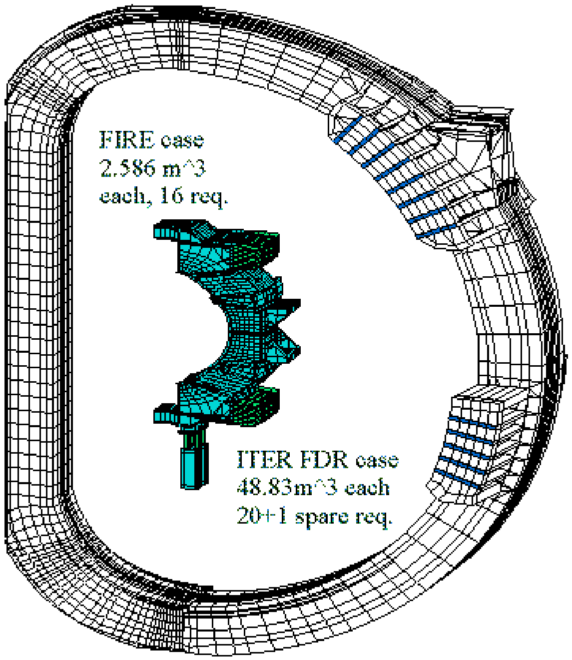
Frictional Restraint at the CS/TF interface Restrains the CS2 Launching load

Recommendation: To minimize vertical slippage, and minimize fault load considerations, use a 15 cm thick Mandrel shell. If you rely on CS2/TF friction, A failure to heat CS2 might produce too little frictional constraint. You would be limited in running a lower TF field because the bucking pressure might be too low

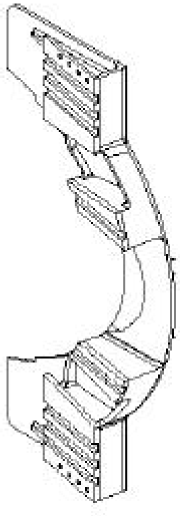


Radial - Vertical Shear Helps Restrain CS2 In B&W Concept.

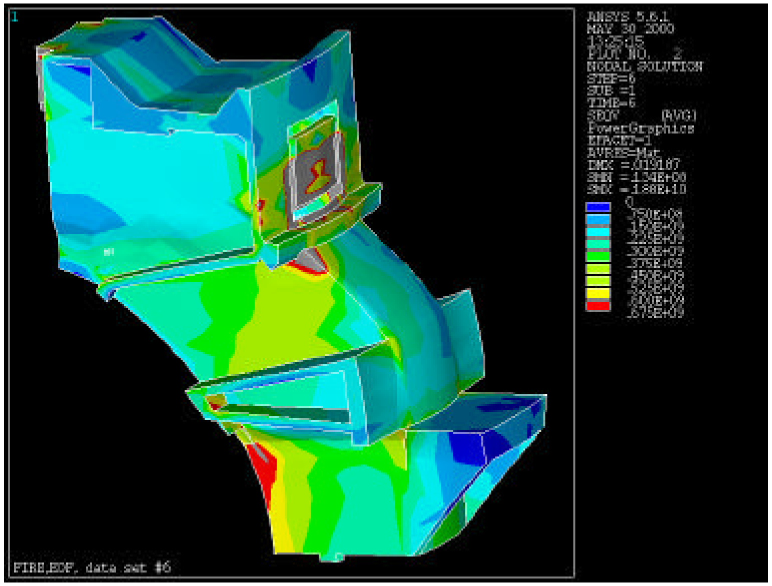
Case Design and Stresses



FDR, FIRE



Case Side Plate Weldment



Von The Case, Red is 675 MPa

50%CW 304 SST

Sm=154 Sm=620MPa at RT

Sm=188 Sm=834MPa at 80K

Outer-Inter-Coil Assemblies can be Cast Thickened.

Case Should be Work Hardened Material

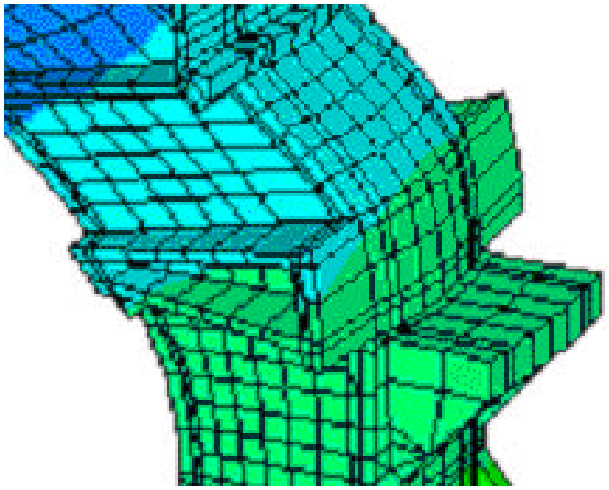
Case Slippage

Case Slippage

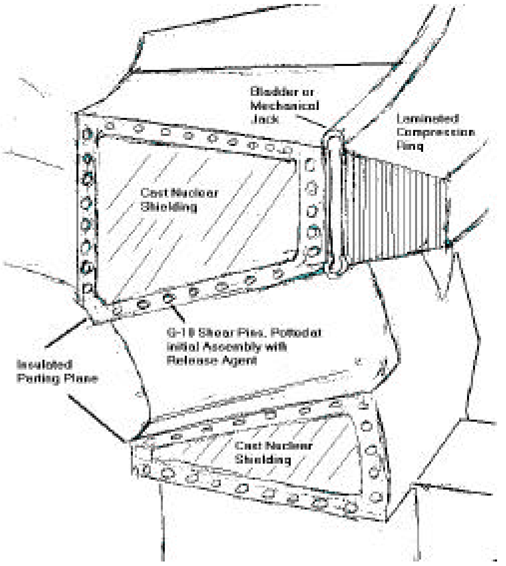
There is slight evidence of slippage in the Outer-Inter-Coil Box Section

A friction coefficient of .3 was assumed at this interface, and it is recommended that :

- Some mechanical shear connections be retained and,
- Higher friction coefficient materials and/or surface preparations be found.
- Shear Pins or Keys are recommended, Even Though Most of the Shear will be taken by Friction
-

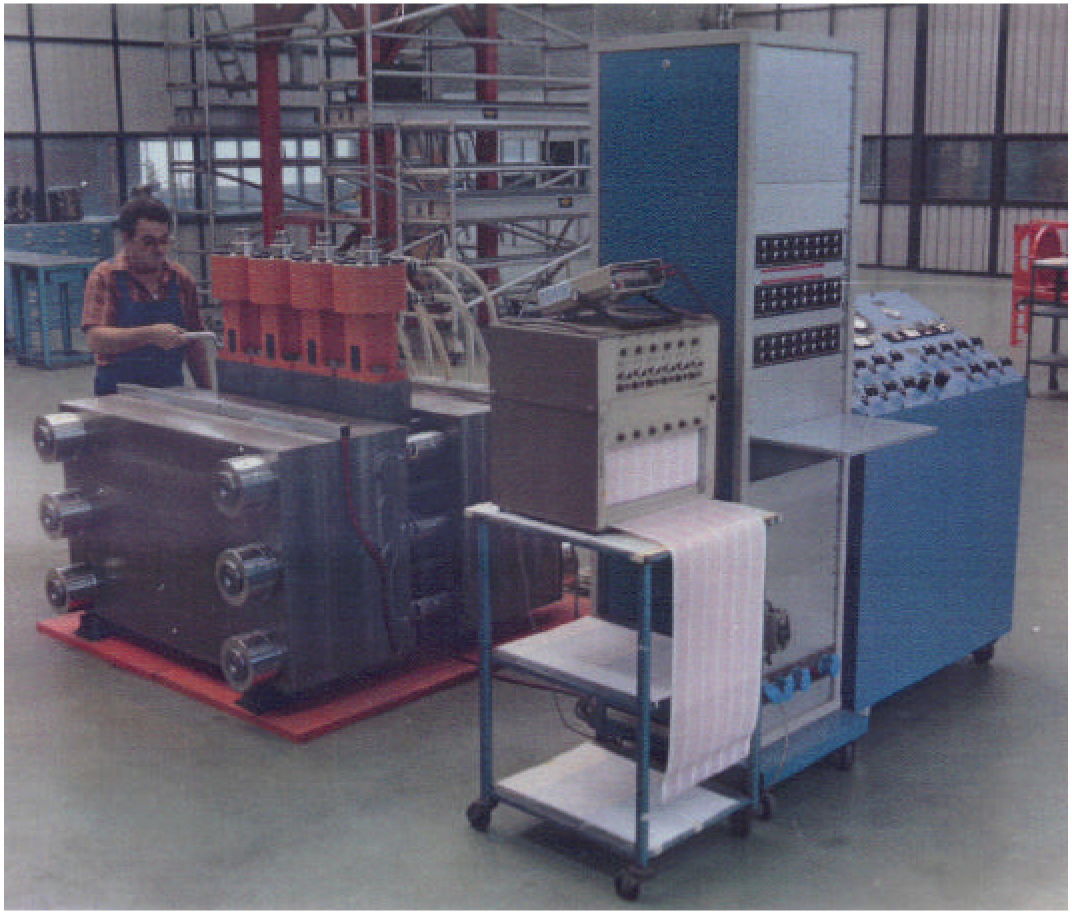


Even With Full Ring Load, Note Toroidal Discontinuity of Vert Disp

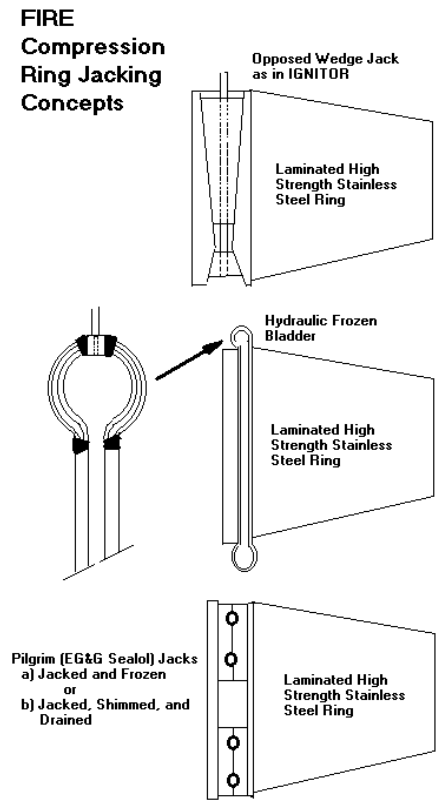


Ring Jacking Mechanism:

A System Exists that Meets FIRE's Needs. Other Systems May Be Possible and Cost Effective.

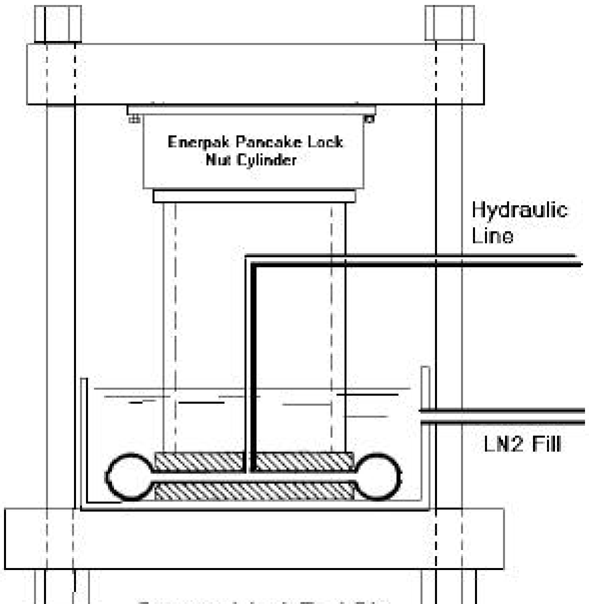


Tests of IGNITOR Jacking System by ANSALDO(?)



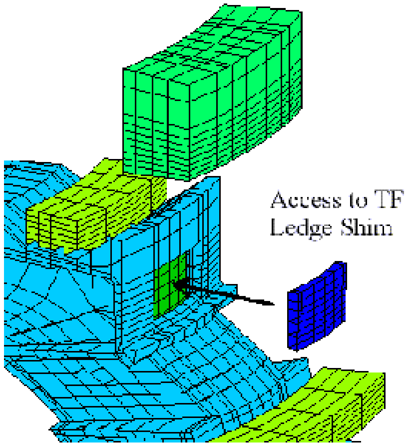
A steel flat jack used in the construction industry

Proposed Fluid Jack and Bladder R&D



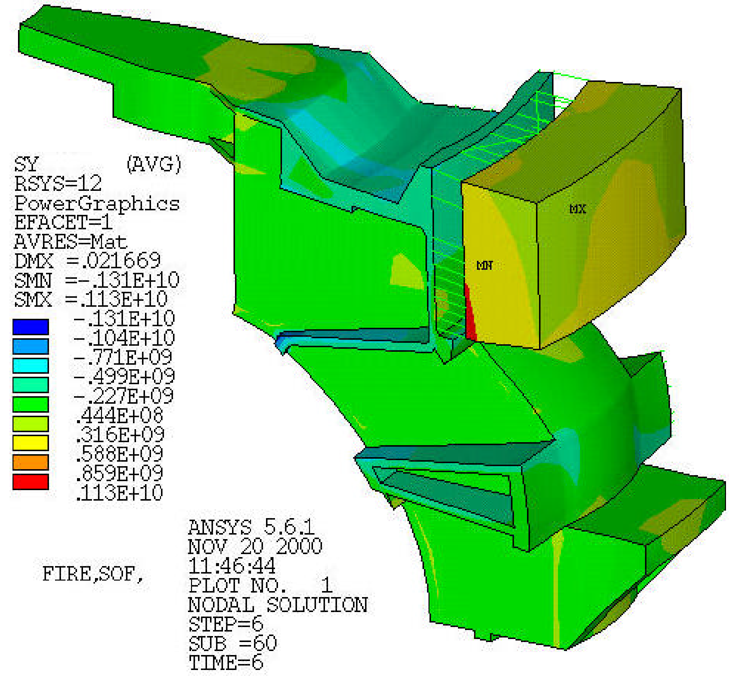
Proposed Jack Test Rig

To simulate the stroke, long tie rods with the correct compliance could be used. Alternatively, the bladder jack could work against a conventional hydraulic jack that would be backed off as the bladder jack was pressurized. After the bladder is tested, the jack could be frozen with it's hydraulic fluid, to evaluate it's feasibility for the ring loading application.



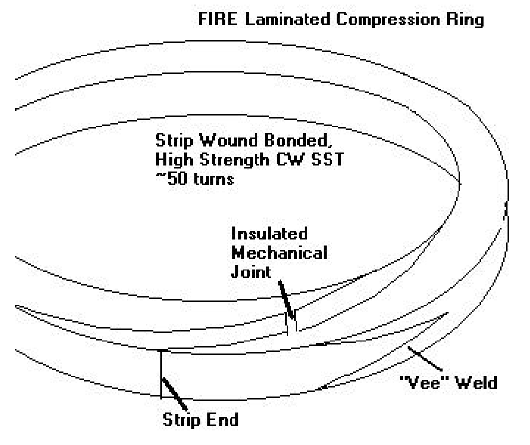
Epoxy Bladder, and Possibly Freezable Bladder Jacks Could be Used to Obtain Proper Load-Share Between Wedged Case and Wedged TF Inner Corners

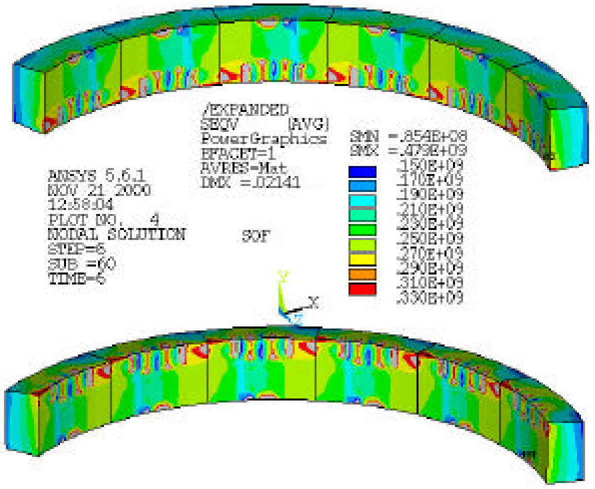
Ring Stresses



Run #60 Hoop Stress in Ring and Case, Full Ring Extension at SOF, Ave Hoop is about 600 MPa

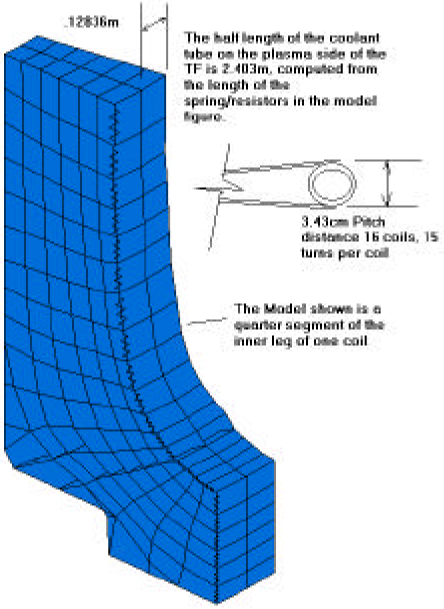
#64 (1/4 Ring Extension)



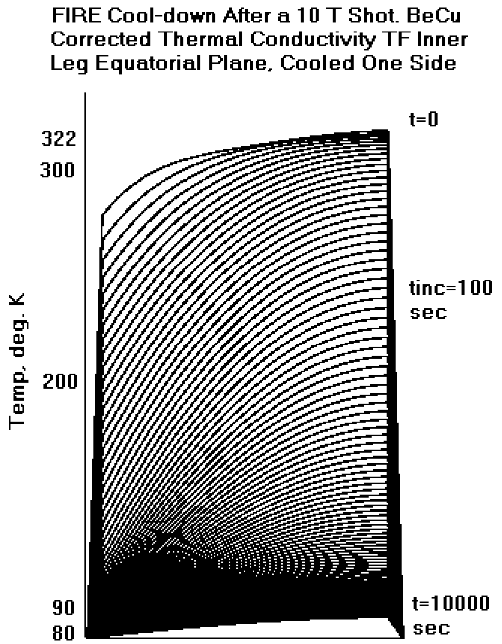


Externsion, Ave VM (Mostly Hoop) is about 220

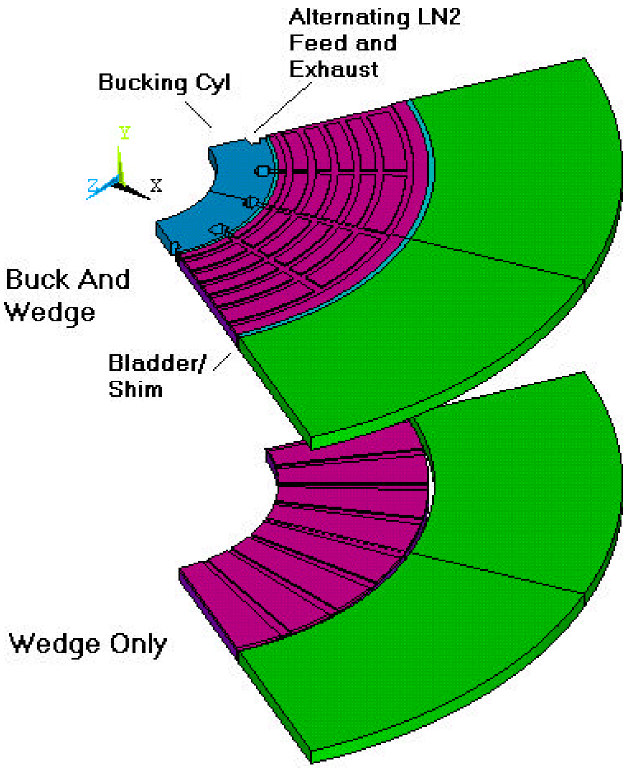
Coil Cool-Down



Inner Leg Cooling Tube Dimensions



For FIRE, with some form of cooling "fin" detail on the ID, 6000 sec, or 1 Hr and 40 min is required for a copper coil and 10000 sec. or about 3 hours for the BeCu TF inner leg material.



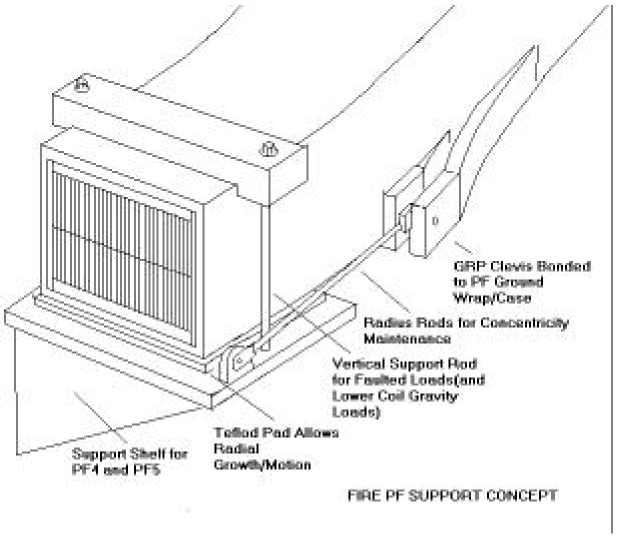
CS Cooling Arrangements: Channels are Pancake to Pancake Insulation Sheets Which are Bonded between Double Pancakes. While conduction

the conduction path is lower than in the TF.

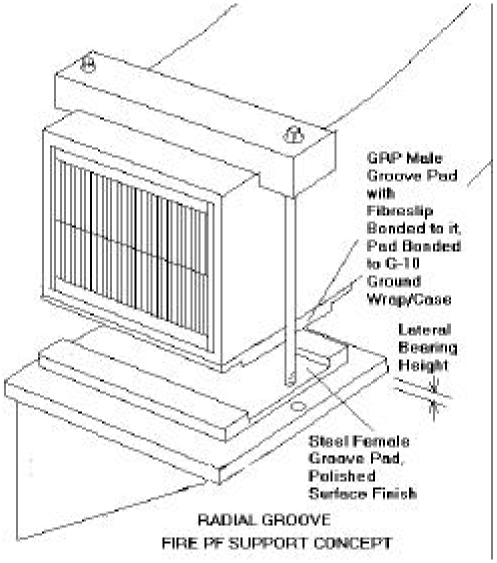
PF Coil Supports

Concentricity Maintenance

The radial grooves used in the CIT/BPX arrangement may be subject to binding and alignment problems. This was the motivation for considering the use a system of radius rods. This type of support was used for the GEM detector, and is used for support of large superconducting solenoids. In this concept there would be as a minimum, one unidirectional tangential radius rod in the shadow of each TF coil.



Has Limited Lateral Load Capacity



Has a Large Lateral Load Capacity, But Subject to Binding?

Strap Type PF Support Used on TFTR - Photo taken in

Concept Also Used For ITER, - Has Good Lateral Load Capacity, -Still Possible for FIRE

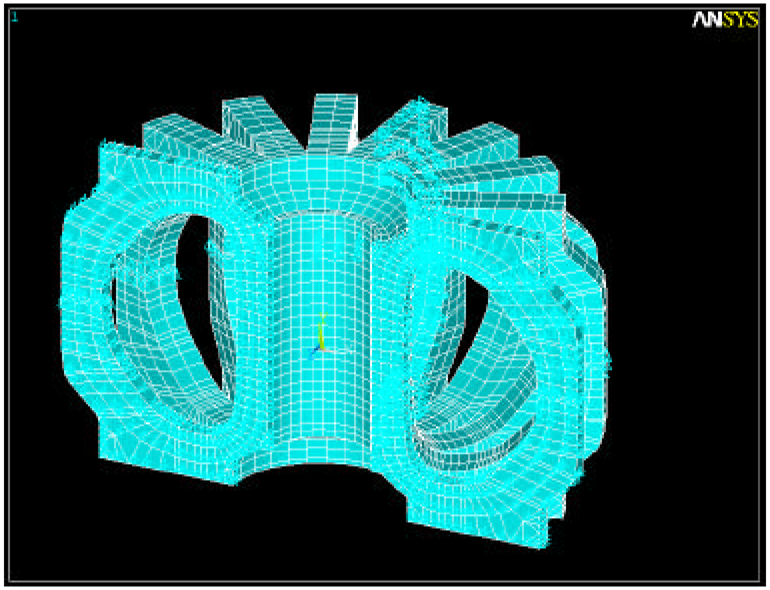
Fault Analysis

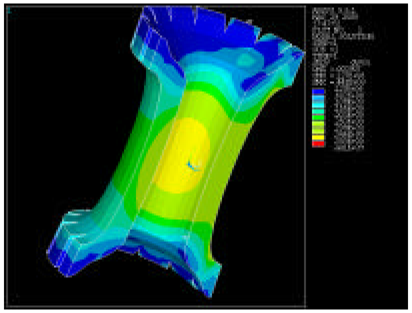
Survivability in Off-Normal or Faulted Loading Is Required by the FIRE Criteria Document.

Where Faulted Loads, Produce No Permanent Damage, It is Also is a Measure of Design Margin.

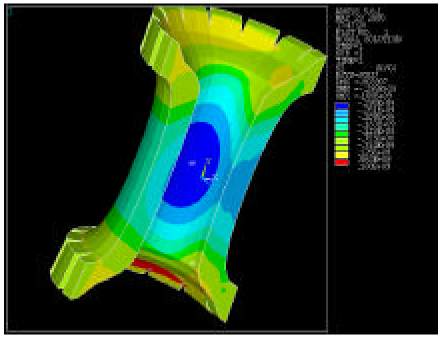
Simplified Fault Analysis

Model and Current/Loading	Peak TF Stress
Nominal 10T No Tierod Detailed Model	469 MPa
Fault Model Nominal 10T	522 MPa
Fault Model Single Coil 10% Over Nominal	533 MPa
Fault Model Single Coil 20% Over Nominal- the Rest 20% Under	441 MPa

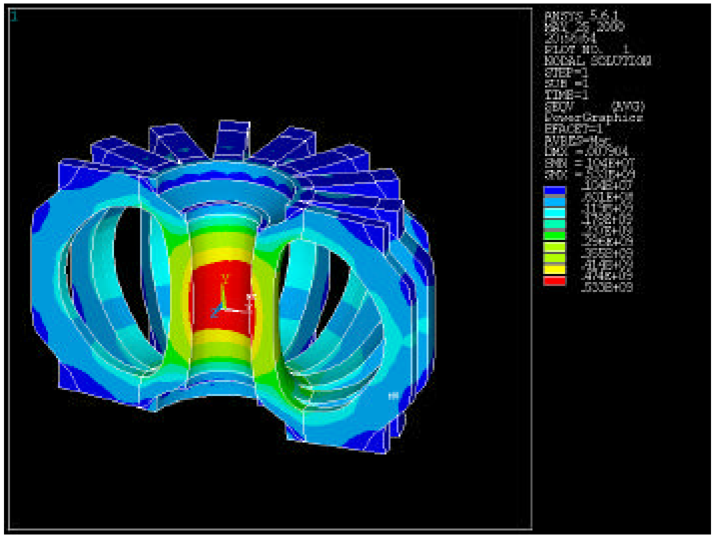




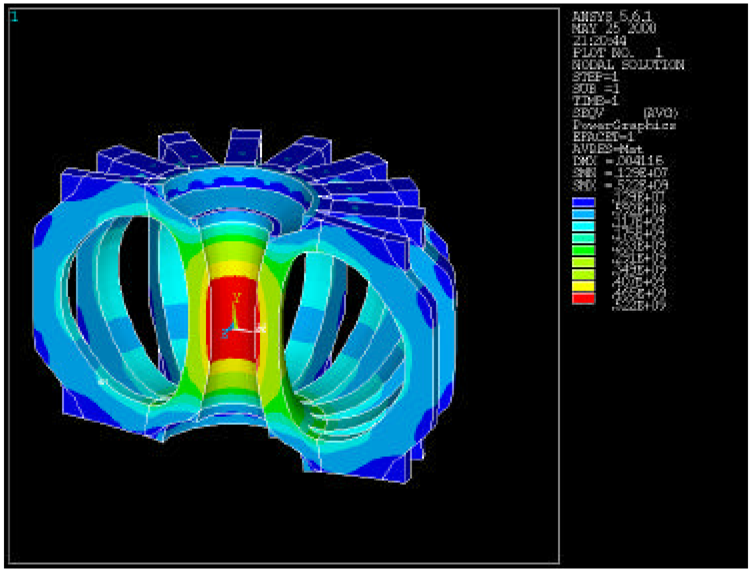
Fault Model Single Coil 20% Over Nominal- the Rest 20% Under - Von Mises Stresses



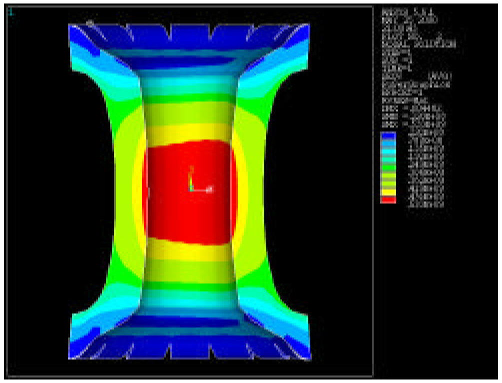
Fault Model Single Coil 20% Over Nominal- the Rest 20% Under - Wedge Stresses



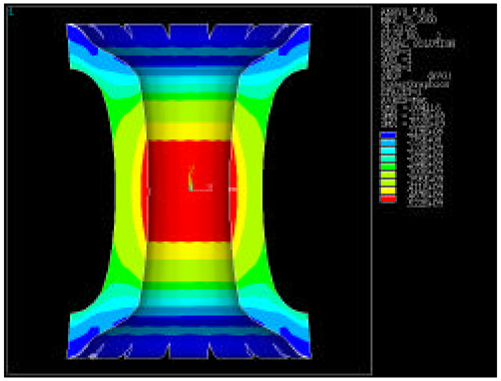
Single Coil 10% over Nominal 10T Current 533 MPa VM Simplified Model - No Case



MPa VM - Simplified Model - No Case



Single Coil 10% over Nominal 10T Current - 533



Baseline 10 T 522 MPa VM

Conclusions:

The 12T Ro=2.0mWedged BeCu Design is At it's Design Allowable

The 11.5 T Ro=2.0m Bucked and Wedged OFHC Copper Design is At Its' Design Allowable

The TF Field Limit Loads of the Two Designs Have been Estimated:

Parameter	2.0 Wedged 68% BeCu	Bucked&Wedged OFHC Copper
TF Bo Limit Loads:	>~14T (Higher if Collapse onto the CS is Allowed)	~16T

FIRE* Variants May be Scaled from These Two Configurations.

Addition of the Structural Ring Provides Design Freedom in Supporting the OOP Loading in TF Inner Leg and in the Case Outer-Intercoil Structures.

Fit-Up Issues of Wedged and Bucked and Wedged are a "Wash" The High Performance Wedged Machine Must have Greater Precision of the Wedged Faces if The Full Strength of the BeCu is to be Used Due to Insulation Compression Limitations. The Bucked and Wedged OFHC Cu TF Operates at a Lower Wedge Pressure, and the Copper Yields to relieve High Spots.

Radial Fields in the Bore of the Segmented Solenoid Will Necessitate Full Height Lateral Support of the Leads. Designs are required to Support the Vertical Loading Developed at the "Break-Out"

FIRE is Robust Against Presently Postulated Faults.

Addition of a Bucking Cylinder in the Bore of the CS is Required to Demonstrate a Limit Load Factor of 2.0 for the Bucked and Wedged Configuration, And Also Provides a Mechanism for Lateral Support of the Leads, and in Concert with the TF, Limits Differential Radial Motion of the CS Segments.